Dihadron production in proton-nucleus collisions

Farid Salazar

FS: I need to add proper references... and double check the formulas (i.e. rederive the results).

CONTENTS

I. PARTONIC CROSS-SECTION

Kinematics: $\boldsymbol{p_{1\perp}}$ and $\boldsymbol{p_{2\perp}}$ are the transverse momenta of the produced partons respectively, and y_1 and y_2 the corresponding rapidities.

The mean transverse momentum is:

$$\boldsymbol{P}_\perp = (1-z)\boldsymbol{p_{1\perp}} - z\boldsymbol{p_{2\perp}} \tag{1}$$

and the momentum imbalance is

$$\boldsymbol{k}_\perp = \boldsymbol{p_{1\perp}} + \boldsymbol{p_{2\perp}} \tag{2}$$

The longitudinal momentum fraction of the first parton relative to the incoming parton

$$z = \frac{p_{1\perp}e^{y_1}}{p_{1\perp}e^{y_1} + p_{2\perp}e^{y_2}} \tag{3}$$

The longitudinal momentum fraction of the gluon probed is

$$x_A = \frac{1}{\sqrt{s}}\left(p_{1\perp}e^{-y_1} + p_{2\perp}e^{-y_2}\right) \tag{4}$$

Keeping only leading terms in N_c and ignoring the angular dependence Φ between $\boldsymbol{P}_\perp$ and $\boldsymbol{k}_\perp$:

$$\frac{\mathrm{d}\sigma^{qA\to qgX}}{\mathrm{d}^2\boldsymbol{P}_\perp \mathrm{d}^2\boldsymbol{k}_\perp \mathrm{d}y_1\mathrm{d}y_2} = \frac{\alpha_s^2}{2C_F}\frac{z(1-z)}{\boldsymbol{P}_\perp^4}P_{gq}(z)\left[(1-z)^2\mathcal{F}_{qg}^{(1)}(x_A,\boldsymbol{k}_\perp)+\mathcal{F}_{qg}^{(2)}(x_A,\boldsymbol{k}_\perp)\right] \tag{5}$$

$$\frac{\mathrm{d}\sigma^{gA\to q\bar{q}X}}{\mathrm{d}^2\boldsymbol{P}_\perp \mathrm{d}^2\boldsymbol{k}_\perp \mathrm{d}y_1\mathrm{d}y_2} = \frac{\alpha_s^2}{2C_F}\frac{z(1-z)}{\boldsymbol{P}_\perp^4}P_{qg}(z)\left[((1-z)^2+z^2)\mathcal{F}_{gg}^{(1)}(x_A,\boldsymbol{k}_\perp)+2z(1-z)\mathcal{F}_{gg}^{(2)}(x_A,\boldsymbol{k}_\perp)\right] \tag{6}$$

$$\frac{\mathrm{d}\sigma^{gA\to ggX}}{\mathrm{d}^2\boldsymbol{P}_\perp \mathrm{d}^2\boldsymbol{k}_\perp \mathrm{d}y_1\mathrm{d}y_2} = \frac{\alpha_s^2}{2C_F}\frac{z(1-z)}{\boldsymbol{P}_\perp^4}P_{gg}(z)\left[((1-z)^2+z^2)\mathcal{F}_{gg}^{(1)}(x_A,\boldsymbol{k}_\perp)+2z(1-z)\mathcal{F}_{gg}^{(2)}(x_A,\boldsymbol{k}_\perp)+\mathcal{F}_{gg}^{(6)}(x_A,\boldsymbol{k}_\perp)\right] \tag{7}$$

with $C_F=(N_c^2-1)/(2N_c)$, $N_c=3$, and $\alpha_s=g^2/(4\pi)\approx 0.15$.

The splitting functions $P(z)$ are

$$P_{gq}(z)=C_F\frac{1+(1-z)^2}{z} \tag{8}$$

$$P_{qg}(z)=C_F\frac{z^2+(1-z)^2}{2} \tag{9}$$

$$P_{gg}(z)=2N_c\left[\frac{z}{1-z}+\frac{1-z}{z}+z(1-z)\right] \tag{10}$$

The TMDs $\mathcal{F}(x_A,\boldsymbol{k}_\perp)$ for the quark-gluon initiated channels are

$$\mathcal{F}_{qg}^{(1)}(x_A,\boldsymbol{k}_\perp)=\frac{N_c\boldsymbol{k}_\perp^2 S_\perp}{2\pi^2\alpha_s}F(x_A,\boldsymbol{k}_\perp) \tag{11}$$

$$\mathcal{F}_{qg}^{(2)}(x_A,\boldsymbol{k}_\perp)=\int \mathrm{d}^2\boldsymbol{q}_\perp \mathcal{F}_{WW}(x_A,\boldsymbol{q}_\perp)F(x_A,\boldsymbol{k}_\perp-\boldsymbol{q}_\perp) \tag{12}$$

and those for the gluon-gluon initiated channels are

$$\mathcal{F}_{gg}^{(1)}(x_A,\boldsymbol{k}_\perp)=\int \mathrm{d}^2\boldsymbol{q}_\perp \mathcal{F}_{qg}^{(1)}(x_A,\boldsymbol{k}_\perp)F(x_A,\boldsymbol{k}_\perp-\boldsymbol{q}_\perp) \tag{13}$$

$$\begin{aligned}\mathcal{F}_{gg}^{(2)}(x_A,\boldsymbol{k}_\perp)&=-\int \mathrm{d}^2\boldsymbol{q}_\perp \frac{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)\cdot\boldsymbol{q}_\perp}{\boldsymbol{q}_\perp^2}\mathcal{F}_{qg}^{(1)}(x_A,\boldsymbol{k}_\perp)F(x_A,\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)\\ &=\mathcal{F}_{gg}^{(2)}(x_A,\boldsymbol{k}_\perp)-\mathcal{F}_{adj}(x_A,\boldsymbol{k}_\perp)\end{aligned} \tag{14}$$

$$\mathcal{F}_{gg}^{(6)}(x_A,\boldsymbol{k}_\perp)=\int \mathrm{d}^2\boldsymbol{q}_\perp \mathrm{d}^2\boldsymbol{q}'_\perp \mathcal{F}_{WW}(x_A,\boldsymbol{q}_\perp)F(x_A,\boldsymbol{q}'_\perp)F(x_A,\boldsymbol{k}_\perp-\boldsymbol{q}_\perp-\boldsymbol{q}'_\perp) \tag{15}$$

where

$$F(x_A,\boldsymbol{k}_\perp)=\int\frac{\mathrm{d}^2\boldsymbol{r}_\perp}{(2\pi)^2}e^{-i\boldsymbol{k}_\perp\cdot\boldsymbol{r}_\perp}S(x_A,\boldsymbol{r}_\perp) \tag{16}$$

$$\mathcal{F}_{WW}(x_A,\boldsymbol{k}_\perp)=\frac{C_F S_\perp}{2\pi^2\alpha_s}\int\frac{\mathrm{d}^2\boldsymbol{r}_\perp}{(2\pi)^2}e^{-i\boldsymbol{k}_\perp\cdot\boldsymbol{r}_\perp}\frac{4}{\boldsymbol{r}_\perp^2}\left[1-(S(x_A,\boldsymbol{r}_\perp))^2\right] \tag{17}$$

$$\mathcal{F}_{adj}(x_A,\boldsymbol{k}_\perp)=\frac{C_F S_\perp \boldsymbol{k}_\perp^2}{2\pi^2\alpha_s}\int\frac{\mathrm{d}^2\boldsymbol{r}_\perp}{(2\pi)^2}e^{-i\boldsymbol{k}_\perp\cdot\boldsymbol{r}_\perp}\left(S(x_A,\boldsymbol{r}_\perp)\right)^2 \tag{18}$$

where $S_\perp$ is the transverse area of the nucleus $S_\perp=\pi R_A^2$, with $R_A=1.1$ fm $\mathrm{A}^{1/3}$. For gold $A=197$.

The two-point function $S(x_A,\boldsymbol{r}_\perp)$ (dipole) of light-like Wilson lines. In the MV model

$$S(x_A,\boldsymbol{r}_\perp)=\exp\left[-\frac{1}{4}\boldsymbol{r}_\perp^2 Q_s^2(x_A)\ln\left(\frac{1}{\Lambda r_\perp}+e\right)\right] \tag{19}$$

where $\Lambda=0.241$ GeV, and

$$Q_s^2(x_A)=(x_0/x_A)^\lambda Q_{s0}^2 \tag{20}$$

with $\lambda=0.3$, $x_0=0.01$, $Q_{s0}^2=0.15$ GeV^2 $\kappa\mathrm{A}^{1/3}$, and $\kappa=0.5$ (for a large nucleus).

II. FROM PARTONS TO HADRONS

III. DOUBLE PARTON SCATTERING CONTRIBUTION

IV. INCLUDING SUDAKOV FACTOR

FS: In progress

V. TO DO:

1. Bonus: Use the Fourier transform trick to express the TMDs as Fourier transforms in coordinate space (convolution theorem).
2. Plot the different TMD distributions as a function of $\boldsymbol{k}_\perp$ for different values of $x_A \leq 0.01$.
3. Compute the partonic cross-sections in Eqs. (5),(6) and (7). Let $\sqrt{s} = 200$ GeV (RHIC), $A = 197$ (gold nucleus/ion) use the MV model for the dipole. Plot the cross-section as a function of the azimuthal angle ϕ between $\boldsymbol{p_{1\perp}}$ and $\boldsymbol{p_{2\perp}}$.

   Note:

$$P_\perp^2 = |(1-z)\boldsymbol{p_{1\perp}} - z\boldsymbol{p_{2\perp}}|^2 = (1-z)^2 p_{1\perp}^2 + z^2 p_{2\perp}^2 - 2z(1-z)p_{1\perp}p_{2\perp}\cos(\phi) \tag{21}$$
$$k_\perp^2 = |\boldsymbol{p_{1\perp}} + \boldsymbol{p_{2\perp}}|^2 = p_{1\perp}^2 + p_{2\perp}^2 + 2p_{1\perp}p_{2\perp}\cos(\phi) \tag{22}$$

   Choose different combinations of $p_{1\perp}$ and $p_{2\perp}$ e.g.

$$(p_{1\perp}, p_{2\perp}) = (1.0, 1.1) \text{ GeV} \tag{23}$$
$$= (1.0, 1.6) \text{ GeV} \tag{24}$$
$$= (1.5, 1.6) \text{ GeV} \tag{25}$$
$$= (1.5, 2.1) \text{ GeV} \tag{26}$$

   and different rapidities y_1, y_2:

$$(y_1, y_2) = (2.0, 2.0) \tag{27}$$
$$= (2.0, 2.5) \tag{28}$$
$$= (2.0, 3.0) \tag{29}$$

   Make sure that these kinematical variables do not exceed $x_A \leq 0.01$ and $x_p \leq 1$ where

$$x_p = \frac{1}{\sqrt{s}}\left(p_{1\perp}e^{y_1} + p_{2\perp}e^{y_2}\right) \tag{30}$$

   In the plot let $\phi \in (\pi/4, 3\pi/4)$.
4. Bonus: You can also try different center of mass energies $\sqrt{s}$ (e.g. LHC energies), and different rapidities, transverse momenta.
5. Bonus: You can try the GBW model, or even better the rcBK [1]!

[1] Strictly speaking the relations for the TMDs Eqs. should be modified when using rcBK

VI. ADDITIONAL POTENTIAL IMPROVEMENTS

1. The partonic cross-sections we derived only depend on $P_\perp$ and $k_\perp$ and not on the angle Φ between $\boldsymbol{P}_\perp$ and $\boldsymbol{k}_\perp$. We can include correlations, i.e. dependence on the angle Φ between $\boldsymbol{P}_\perp$ and $\boldsymbol{k}_\perp$, by incorporating the "linearly" polarized distributions. Our TMDs are unpolarized.

2. The expressions we use above are valid only for $k_\perp \lesssim P_\perp$ (i.e. for $\phi \sim \pi$, back-to-back production), we can include the so called "kinematic power corrections" to extend the domain of validity beyond small momentum imbalance condition $k_\perp \lesssim P_\perp$.

3. Include terms beyond the leading N_c approximation.

VII. USEFUL REFERENCES

- Recent experimental analysis of RHIC semi-inclusive dihadron data [1].

- Connection between small-x CGC amplitudes and TMD for various $2 \to 2$ channels [2] (see also [3, 4]).

- Sudakov factors for various $2 \to 2$ channels [5] and a short version [6].

- One of the very first papers suggesting the study of azimuthal correlations in dihadron production at RHIC [7]

- First phenomenological analyses (no Sudakov, simple dipole model, only including limited channels. Very first analysis [8] (be aware it has several errors...). Full CGC at LO at large N_c, only quark initiated channel is considered [9]. TMD calculation using GBW model and including all relevant channels [10] includes a nice discussion of double parton contribution.

- Theory paper with all TMDs necessary for dihadron production in proton-nucleus collisions, including finite N_c corrections [11]. A nice review of TMDs with numerical study using JIMWLK in [12].

- More recent phenomenological analyses: GBW model, large N_c and Sudakov in [13]. TMD factorization with rcBK dipole, large N_c and no Sudakov [14].

- Predictions for dihadron suppression the EIC using GBW + Sudakov [13]. A similar study for dijets including a subset of kinematic power corrections [15].

- Theory paper that discusses ITMD [16] in proton-nucleus collisions.

- Kinematic power and genuine saturation corrections [17], see also [18]

- Forward-forward dijet in pp and pA at the LHC using ITMD + Sudakov, compared to data. [19]. See earlier work [20] which does not include Sudakov and not compared to data. See also forward-central dijet correlations [21, 22] including predictions. See also study within HEF using unintegrated gluon distribution [23]

- Forward dijet production in UPCs [24] using ITMD + Sudakov no comparison to data.

- Alternatives scenarios to azimuthal decorrelations [25, 26]

- Double parton scattering in proton-nucleus collisions [27]

- Initial conditions: [28]

A. Other useful refs

- Two particle azimuthal harmonics in pA [29]
- Coherent energy loss dihadrons at the EIC [30]
- NLO real corrections for dijets/dihadrons in pA [31]
- Prompt photon-jet correlations in DIS [32], prompt photon-hadron correlations in proton-nucleus [33–35]
- Origin of azimuthal correlations [36]

Appendix A: Beyond MV: TMDs from running coupling BK

$$\alpha_s \mathcal{F}_{qg}^{(1)}(x, \boldsymbol{k}_\perp) = \frac{N_c S_\perp}{2\pi^2} \int \frac{r_\perp \mathrm{d}r_\perp}{2\pi} J_0(k_\perp r_\perp) \nabla_\perp^2 \left[1 - S(x, r_\perp)\right] \tag{A1}$$

$$\alpha_s \mathcal{F}_{qg}^{(2)}(x, \boldsymbol{k}_\perp) = \frac{C_F S_\perp}{2\pi^2} \int \frac{r_\perp \mathrm{d}r_\perp}{2\pi} J_0(k_\perp r_\perp) \mathcal{K}(x, r_\perp) \left[1 - (S(x, r_\perp))^{N_c/C_F}\right] S(x, r_\perp) \tag{A2}$$

$$\alpha_s \mathcal{F}_{gg}^{(1)}(x, \boldsymbol{k}_\perp) = \frac{N_c S_\perp}{2\pi^2} \int \frac{r_\perp \mathrm{d}r_\perp}{2\pi} J_0(k_\perp r_\perp) S(x, r_\perp) \nabla_\perp^2 \left[1 - S(x, r_\perp)\right] \tag{A3}$$

$$\alpha_s \mathcal{F}_{adj}(x, \boldsymbol{k}_\perp) = \frac{C_F S_\perp}{2\pi^2} \int \frac{r_\perp \mathrm{d}r_\perp}{2\pi} J_0(k_\perp r_\perp) \nabla_\perp^2 \left[1 - (S(x, r_\perp))^{N_c/C_F}\right] \tag{A4}$$

$$\alpha_s \mathcal{F}_{WW}(x, \boldsymbol{k}_\perp) = \frac{C_F S_\perp}{2\pi^2} \int \frac{r_\perp \mathrm{d}r_\perp}{2\pi} J_0(k_\perp r_\perp) \mathcal{K}(x, r_\perp) \left[1 - (S(x, r_\perp))^{N_c/C_F}\right] \tag{A5}$$

$$\alpha_s \mathcal{F}_{gg}^{(6)}(x, \boldsymbol{k}_\perp) = \frac{C_F S_\perp}{2\pi^2} \int \frac{r_\perp \mathrm{d}r_\perp}{2\pi} J_0(k_\perp r_\perp) \mathcal{K}(x, r_\perp) \left[1 - (S(x, r_\perp))^{N_c/C_F}\right] (S(x, r_\perp))^{N_c/C_F} \tag{A6}$$

where

$$\nabla_\perp^2 = \frac{\partial^2}{\partial r_\perp^2} + \frac{1}{r_\perp} \frac{\partial}{\partial r_\perp} \tag{A7}$$

$$\mathcal{K}(x, r_\perp) = \frac{\nabla_\perp^2 \Gamma(x, r_\perp)}{\Gamma(x, r_\perp)} \tag{A8}$$

$$\Gamma(x, r_\perp) = -\log\left[S(x, r_\perp)\right] \tag{A9}$$

1. To do:

1. Compute distributions above using the GBW model.

$$S_{\mathrm{GBW}}(x, r_\perp) = \exp\left[-\frac{1}{4} Q_s^2(x) r_\perp^2\right] \tag{A10}$$

with $Q_s^2(x) = Q_{s0}^2 (x_0/x)^\lambda$. Let $Q_{s0}^2 = 1.0\ \mathrm{GeV}^2$, $x_0 = 0.01$, and $\lambda = 0.3$.

2. Compute distributions above using the MV model

$$S_{\rm MV}(x,r_\perp) = \exp\left[-\frac{1}{4}Q_s^2(x)r_\perp^2 \log\left(\frac{1}{\Lambda r_\perp}+e\right)\right] \tag{A11}$$

with $\Lambda = 0.241$ GeV and $Q_s^2(x) = Q_{s0}^2(x_0/x)^\lambda$. Let $Q_{s0}^2 = 0.6$ GeV^2, $x_0 = 0.01$, and $\lambda = 0.3$.

3. Compute distributions above using rcBK with MV initial conditions as above.

Might be convenient to fit the rcBK data first with a "modified" MV dipole that includes $r_\perp$ dependence on the saturation scale:

$$S_{\rm rcBK}(x,r_\perp) = \exp\left[-\frac{1}{4}Q_s^2(x,r_\perp)r_\perp^2 \log\left(\frac{1}{\Lambda r_\perp}+e\right)\right] \tag{A12}$$

with $Q_s^2(x,r_\perp) = Q_{s0}^2(x_0/x)^{\lambda\exp(-c_1 r_\perp)/(c_2 r_\perp)^\kappa}$

4. In all cases verify if all the distributions have the same behavior at large $\boldsymbol{k}_\perp$

5. An efficient way to compute the integral is to integrate over the zeros of the Bessel function, so that we can avoid the oscillatory behavior.

$$\begin{aligned} I &= \int_0^\infty u\mathrm{d}u J_0(u) f(u) \\ &= \lim_{N\to\infty}\sum_{j=1}^{N}\int_{u_j}^{u_{j+1}} u\mathrm{d}u J_0(u) f(u) \end{aligned} \tag{A13}$$

See e.g.

`https://www.ipht.fr/Pisp/francois.gelis/Soft/Fourier/index.php`

Appendix B: Results for TMDs using the MV model

If

$$S(x,r_\perp) = \exp\left[-\frac{1}{4}Q_s^2(x)r_\perp^2 \log\left(\frac{1}{\Lambda r_\perp}+e\right)\right] \tag{B1}$$

then

$$\mathcal{K}(x,r_\perp) = \frac{4}{r^2}\left[1 - \frac{4+3e\Lambda r_\perp}{4(1+e\Lambda r_\perp)^2\log(\frac{1}{\Lambda r_\perp}+e)}\right] \tag{B2}$$

$$\begin{aligned} \nabla_\perp^2\left[1-S(x,r_\perp)\right] &= Q_s^2 \exp\left[-\frac{1}{4}Q_s^2(x)r_\perp^2\log\left(\frac{1}{\Lambda r_\perp}+e\right)\right] \\ &\times\left\{\log\left(\frac{1}{\Lambda r_\perp}+e\right) - \frac{(4+3e\Lambda r_\perp)}{4(1+e\Lambda r_\perp)^2} - \frac{Q_s^2 r^2}{16(1+e\Lambda r_\perp)^2}\left[1-2(1+e\Lambda r_\perp)\log\left(\frac{1}{\Lambda r_\perp}+e\right)\right]^2\right\} \end{aligned} \tag{B3}$$

$$\nabla_\perp^2\left[1-\left(S(x,r_\perp)\right)^{N_c/C_F}\right]=\frac{N_c}{C_F}Q_s^2\exp\left[-\frac{1}{4}\frac{N_c}{C_F}Q_s^2(x)r_\perp^2\log\left(\frac{1}{\Lambda r_\perp}+e\right)\right]$$
$$\times\left\{\log\left(\frac{1}{\Lambda r_\perp}+e\right)-\frac{(4+3e\Lambda r_\perp)}{4(1+e\Lambda r_\perp)^2}-\frac{Q_s^2r^2}{16(1+e\Lambda r_\perp)^2}\frac{N_c}{C_F}\left[1-2(1+e\Lambda r_\perp)\log\left(\frac{1}{\Lambda r_\perp}+e\right)\right]^2\right\} \tag{B4}$$

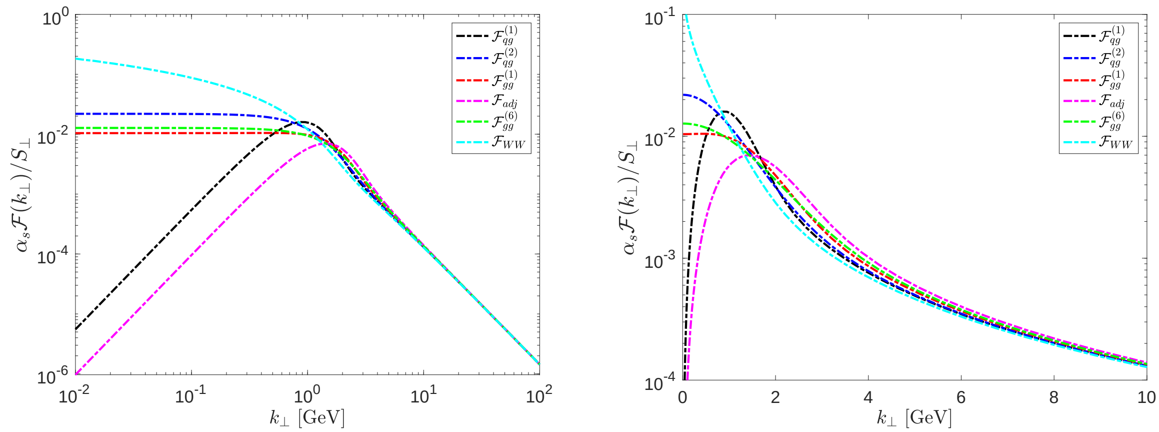

FIG. 1. Small-x transverse momentum distributions $\mathcal{F}(x,k_\perp)$ as a function of $k_\perp$ at $Y=0$ ($x=0.01$) using the MV model. Observe that all distribution tend to the same power law.

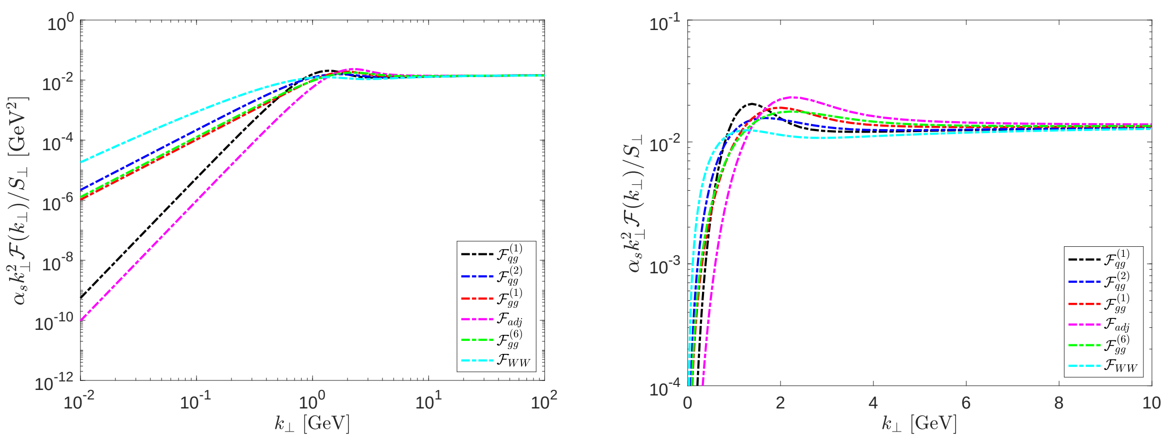

FIG. 2. Small-x transverse momentum distributions $\mathcal{F}(x,k_\perp)$ multiplied by $\boldsymbol{k}_\perp^2$ to manifestly show the power law behavior $1/\boldsymbol{k}_\perp^2$.

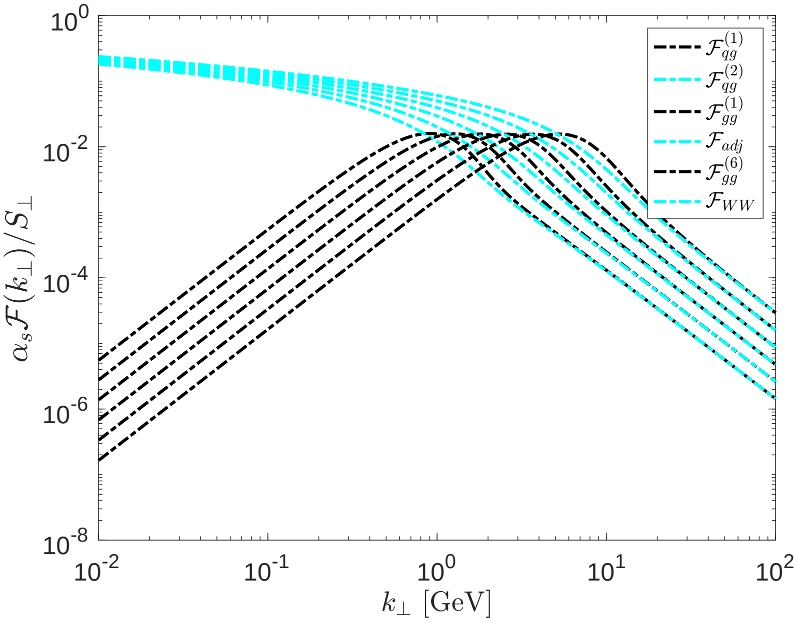

FIG. 3. Small-x transverse momentum distributions $\mathcal{F}(x, k_\perp)$ (only two shown) at different rapidities $Y = 0, 2, 4, 6, 8, 10$ where $Y = \log(x_0/x)$.

Appendix C: Dihadron production for the Electron-Ion Collider

[1] **STAR** Collaboration, M. Abdallah *et al.*, "Evidence for Nonlinear Gluon Effects in QCD and their A Dependence at STAR," `arXiv:2111.10396 [nucl-ex]`.

[2] F. Dominguez, C. Marquet, B.-W. Xiao, and F. Yuan, "Universality of Unintegrated Gluon Distributions at small x," *Phys. Rev. D* **83** (2011) 105005, `arXiv:1101.0715 [hep-ph]`.

[3] F. Dominguez, B.-W. Xiao, and F. Yuan, "k_t-factorization for Hard Processes in Nuclei," *Phys. Rev. Lett.* **106** (2011) 022301, `arXiv:1009.2141 [hep-ph]`.

[4] B.-W. Xiao and F. Yuan, "Non-Universality of Transverse Momentum Dependent Parton Distributions at Small-x," *Phys. Rev. Lett.* **105** (2010) 062001, `arXiv:1003.0482 [hep-ph]`.

[5] A. H. Mueller, B.-W. Xiao, and F. Yuan, "Sudakov double logarithms resummation in hard processes in the small-x saturation formalism," *Phys. Rev. D* **88** no. 11, (2013) 114010, `arXiv:1308.2993 [hep-ph]`.

[6] A. H. Mueller, B.-W. Xiao, and F. Yuan, "Sudakov Resummation in Small-x Saturation Formalism," *Phys. Rev. Lett.* **110** no. 8, (2013) 082301, `arXiv:1210.5792 [hep-ph]`.

[7] C. Marquet, "Forward inclusive dijet production and azimuthal correlations in p(A) collisions," *Nucl. Phys. A* **796** (2007) 41–60, `arXiv:0708.0231 [hep-ph]`.

[8] J. L. Albacete and C. Marquet, "Azimuthal correlations of forward di-hadrons in d+Au collisions at RHIC in the Color Glass Condensate," *Phys. Rev. Lett.* **105** (2010) 162301, `arXiv:1005.4065 [hep-ph]`.

[9] T. Lappi and H. Mäntysaari, "Forward dihadron correlations in deuteron-gold collisions with the Gaussian approximation of JIMWLK," *Nucl. Phys. A* **908** (2013) 51–72, `arXiv:1209.2853 [hep-ph]`.

[10] A. Stasto, B.-W. Xiao, and F. Yuan, "Back-to-Back Correlations of Di-hadrons in dAu Collisions at RHIC," *Phys. Lett. B* **716** (2012) 430–434, `arXiv:1109.1817 [hep-ph]`.

[11] C. Marquet, E. Petreska, and C. Roiesnel, "Transverse-momentum-dependent gluon distributions from JIMWLK evolution," *JHEP* **10** (2016) 065, `arXiv:1608.02577 [hep-ph]`.

[12] E. Petreska, "TMD gluon distributions at small x in the CGC theory," *Int. J. Mod. Phys. E* **27** no. 05, (2018) 1830003, `arXiv:1804.04981 [hep-ph]`.

[13] A. Stasto, S.-Y. Wei, B.-W. Xiao, and F. Yuan, "On the Dihadron Angular Correlations in Forward pA collisions," *Phys. Lett. B* **784** (2018) 301–306, arXiv:1805.05712 [hep-ph].

[14] J. L. Albacete, G. Giacalone, C. Marquet, and M. Matas, "Forward dihadron back-to-back correlations in pA collisions," *Phys. Rev. D* **99** no. 1, (2019) 014002, arXiv:1805.05711 [hep-ph].

[15] A. van Hameren, P. Kotko, K. Kutak, S. Sapeta, and E. Żarów, "Probing gluon number density with electron-dijet correlations at EIC," arXiv:2106.13964 [hep-ph].

[16] P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, and A. van Hameren, "Improved TMD factorization for forward dijet production in dilute-dense hadronic collisions," *JHEP* **09** (2015) 106, arXiv:1503.03421 [hep-ph].

[17] R. Boussarie, H. Mäntysaari, F. Salazar, and B. Schenke, "The importance of kinematic twists and genuine saturation effects in dijet production at the Electron-Ion Collider," *JHEP* **09** (2021) 178, arXiv:2106.11301 [hep-ph].

[18] H. Mäntysaari, N. Mueller, F. Salazar, and B. Schenke, "Multigluon Correlations and Evidence of Saturation from Dijet Measurements at an Electron-Ion Collider," *Phys. Rev. Lett.* **124** no. 11, (2020) 112301, arXiv:1912.05586 [nucl-th].

[19] A. van Hameren, P. Kotko, K. Kutak, and S. Sapeta, "Broadening and saturation effects in dijet azimuthal correlations in p-p and p-Pb collisions at $\sqrt{s} = 5.02$ TeV," *Phys. Lett. B* **795** (2019) 511–515, arXiv:1903.01361 [hep-ph].

[20] A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska, and S. Sapeta, "Forward di-jet production in p+Pb collisions in the small-x improved TMD factorization framework," *JHEP* **12** (2016) 034, arXiv:1607.03121 [hep-ph]. [Erratum: JHEP 02, 158 (2019)].

[21] A. van Hameren, P. Kotko, K. Kutak, and S. Sapeta, "Small-x dynamics in forward-central dijet decorrelations at the LHC," *Phys. Lett. B* **737** (2014) 335–340, arXiv:1404.6204 [hep-ph].

[22] A. van Hameren, P. Kotko, K. Kutak, C. Marquet, and S. Sapeta, "Saturation effects in forward-forward dijet production in p+Pb collisions," *Phys. Rev. D* **89** no. 9, (2014) 094014, arXiv:1402.5065 [hep-ph].

[23] K. Kutak and S. Sapeta, "Gluon saturation in dijet production in p-Pb collisions at Large Hadron Collider," *Phys. Rev. D* **86** (2012) 094043, arXiv:1205.5035 [hep-ph].

[24] P. Kotko, K. Kutak, S. Sapeta, A. M. Stasto, and M. Strikman, "Estimating nonlinear effects in forward dijet production in ultra-peripheral heavy ion collisions at the LHC," *Eur. Phys. J. C* **77** no. 5, (2017) 353, arXiv:1702.03063 [hep-ph].

[25] Z.-B. Kang, I. Vitev, and H. Xing, "Dihadron momentum imbalance and correlations in d+Au collisions," *Phys. Rev. D* **85** (2012) 054024, arXiv:1112.6021 [hep-ph].

[26] H. Xing, Z.-B. Kang, I. Vitev, and E. Wang, "Transverse momentum imbalance of back-to-back particle production in p+A and e+A collisions," *Phys. Rev. D* **86** (2012) 094010, arXiv:1206.1826 [hep-ph].

[27] M. Strikman and W. Vogelsang, "Multiple parton interactions and forward double pion production in pp and dA scattering," *Phys. Rev. D* **83** (2011) 034029, arXiv:1009.6123 [hep-ph].

[28] J. L. Albacete, N. Armesto, J. G. Milhano, P. Quiroga-Arias, and C. A. Salgado, "AAMQS: A non-linear QCD analysis of new HERA data at small-x including heavy quarks," *Eur. Phys. J. C* **71** (2011) 1705, arXiv:1012.4408 [hep-ph].

[29] M. K. Davy, C. Marquet, Y. Shi, B.-W. Xiao, and C. Zhang, "Two particle azimuthal harmonics in pA collisions," *Nucl. Phys. A* **983** (2019) 293–309, arXiv:1808.09851 [hep-ph].

[30] F. Bergabo and J. Jalilian-Marian, "Coherent energy loss effects in dihadron azimuthal angular correlations in Deep Inelastic Scattering at small x," arXiv:2108.10428 [hep-ph].

[31] E. Iancu and Y. Mulian, "Forward dijets in proton-nucleus collisions at next-to-leading order: the real corrections," *JHEP* **03** (2021) 005, arXiv:2009.11930 [hep-ph].

[32] I. Kolbé, K. Roy, F. Salazar, B. Schenke, and R. Venugopalan, "Inclusive prompt photon-jet correlations as a probe of gluon saturation in electron-nucleus scattering at small x," *JHEP* **01** (2021) 052, arXiv:2008.04372 [hep-ph].

[33] J. Jalilian-Marian and A. H. Rezaeian, "Prompt photon production and photon-hadron correlations at RHIC and the LHC from the Color Glass Condensate," *Phys. Rev. D* **86** (2012) 034016, arXiv:1204.1319 [hep-ph].

[34] A. H. Rezaeian, "Semi-inclusive photon-hadron production in pp and pA collisions at RHIC and LHC," *Phys. Rev. D* **86** (2012) 094016, arXiv:1209.0478 [hep-ph].

[35] V. P. Goncalves, Y. Lima, R. Pasechnik, and M. ˇ Sumbera, "Isolated photon production and pion-photon correlations in high-energy pp and pA collisions," *Phys. Rev. D* **101** no. 9, (2020) 094019, arXiv:2003.02555 [hep-ph].

[36] T. Lappi, B. Schenke, S. Schlichting, and R. Venugopalan, "Tracing the origin of azimuthal gluon correlations in the color glass condensate," *JHEP* **01** (2016) 061, arXiv:1509.03499 [hep-ph].