Cold nuclear matter effects on azimuthal decorrelation in heavy-ion collisions

Bin Wu

IGFAE, Universidade De Santiago De Compostela

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arXiv:2407.19243 with Néstor Armesto and Florian Cougoulic.

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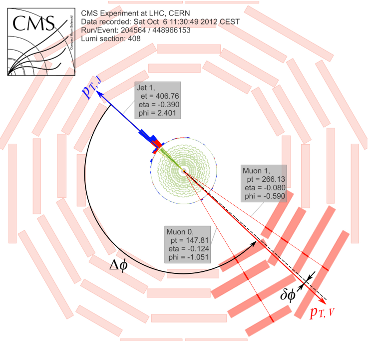
Motivations

Azimuthal decorrelation in pp

Definition: $\Delta\phi \equiv |\phi_V - \phi_J|$ $(\delta\phi \equiv \pi - \Delta\phi)$:

- At LO, $d\sigma/d\delta\phi \sim \delta(\delta\phi)$ (here, we focus on $\delta\phi$ in perturbative regime).
- Radiation or scattering will cause it to expand into non-zero values.

Radiation: dominant in pp



Precise predictions in pp rely on

1. Fixed-order calculations

   NLO, NNLO,$\cdots$

2. Resummation of $\ln\delta\phi$
   - Parton branching method
   - Pythia, Herwig,$\cdots$
   - TMD factorization
   - SCET

The Drell-Yan process: the TMD factorization ($\delta\phi \sim Q_T/Q$)

CSS: J.C. Collins, D.E. Soper and G.F. Sterman, Nucl. Phys. B 250 (1985) 199.

SCET:T. Becher and M. Neubert, Eur. Phys. J. C **71** (2011), 1665 [arXiv:1007.4005 [hep-ph]].$\cdots$

The boson-jet production: the TMD factorization is assumed

P. Sun, B. Yan, C. P. Yuan and F. Yuan, Phys. Rev. D **100** (2019), 054032 [arXiv:1810.03804 [hep-ph]]. ; M. G. A. Buffing, Z. B. Kang, K. Lee and X. Liu, [arXiv:1812.07549 [hep-ph]]; Y. T. Chien, D. Y. Shao and BW, JHEP **11**, 025 (2019) [arXiv:1905.01335 [hep-ph]].

Potential theoretical difficulties for jet processes:

✓ Non-global logarithms: Dasgupta and Salam, Phys. Lett. B **512**, 323-330 (2001).

Could be avoid by using Winner-Take-All (WTA) axis in jet definition.

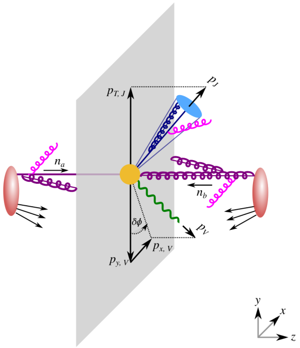
Chien, Rahn, Schrijnder van Velzen, Shao, Waalewijn and BW, Phys. Lett. B **815**, 136124 (2021) [arXiv:2005.12279 [hep-ph]].

Chien, Rahn, Shao, Waalewijn and BW, JHEP 02 (2023), 256 [arXiv:2205.05104 [hep-ph]].

? Factorization breaking by the Glauber mode?

J. Collins and J. W. Qiu, Phys. Rev. D **75** (2007), 114014 [arXiv:0705.2141 [hep-ph]]; T. C. Rogers and P. J. Mulders, Phys. Rev. D **81** (2010), 094006 [arXiv:1001.2977 [hep-ph]].

An all-order resummation formula with the WTA axis using SCET:



Hard function: $\mathcal{H}_{ij\to Vk} \leftarrow$ parton-level $\hat{\sigma}$

Beam functions: $\mathcal{B}_i, \mathcal{B}_j \leftarrow$ TMDs in hadrons

Soft function: $S_{ijk} \leftarrow$ soft radiation

Jet function: $\mathcal{J}_k$ does NOT contain NGLs!

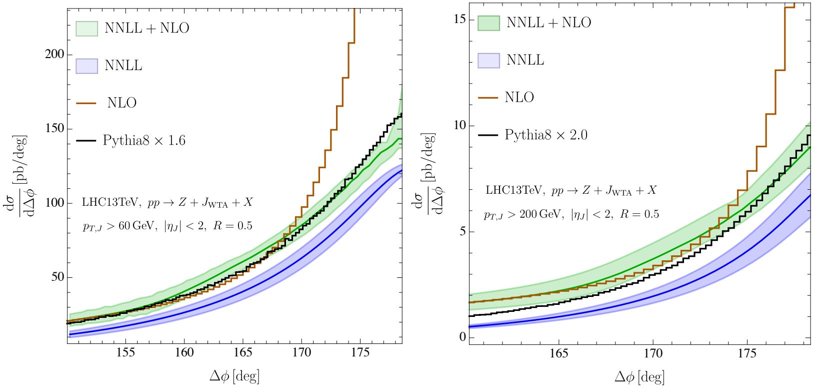
Glauber modes are neglected!

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\,\mathrm{d}y_V\,\mathrm{d}\eta_J} = \int \frac{\mathrm{d}b_x}{2\pi} e^{b_x q_x} \sum_{ijk} \mathcal{H}_{ij\to Vk}(p_{T,V}, y_V - \eta_J)\mathcal{B}_i(x_a, b_x)B_j(x_b, b_x)\mathcal{J}_k(b_x)S_{ijk}(b_x, \eta_J)$$

Chien, Rahn, Schrijnder van Velzen, Shao, Waalewijn and BW, Phys. Lett. B **815**, 136124 (2021) [arXiv:2005.12279 [hep-ph]].

Chien, Rahn, Shao, Waalewijn and BW, JHEP 02 (2023), 256 [arXiv:2205.05104 [hep-ph]].

Theoretical predictions for pp at NNLL + NL0 accuracy

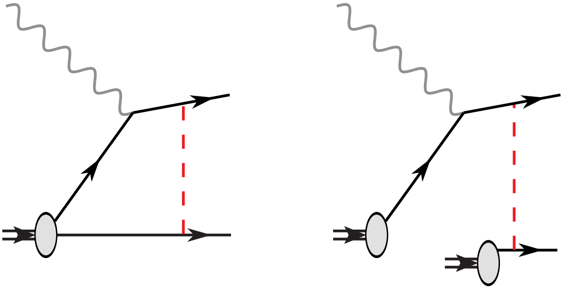


Theoretical uncertainies are under control and can be improved systematically (unless the Glauber modes could spoil the whole results?).

Q_T-distribution in eA

Let us start with DIS a large nucleus:

Glauber topologies:



At this order, it is power suppressed in Λ_{QCD}/Q_T in ep while it is enhanced by the nuclear size in eA.

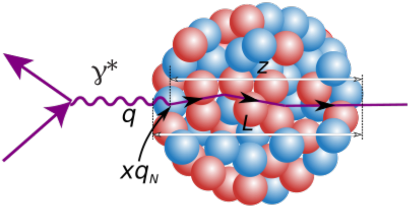
Frame: (sometimes the nucleus is shown at rest)

$$\text{virtual photon:} \qquad q_\mu = \left(q_+, q_- = \frac{Q^2}{2q_+}, q_\perp = 0\right)$$

$$\text{the nucleus:} \qquad P_\mu = \left(\frac{m_A^2}{2P_-}, P_-, P_\perp = 0\right)$$

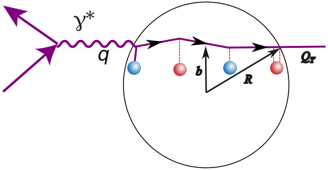
where q_+ and P_- are large.

When $\frac{1}{q^-} \ll L$:



Here, I review briefly an alternative approach to CGC/saturation physics.

When $\frac{1}{q^-} \ll L$:



$$\frac{dN}{d^2bd^2Q_T} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{-iQ_T\cdot x_\perp} \rho_0 x q_N\left(x\right) \int_0^L dz \underbrace{e^{-\frac{1}{4}\hat{q}x_\perp^2 z}}_{S(x_\perp, z)}$$

Kovchegov and Mueller, Nucl. Phys. B **529**, 451 (1998).

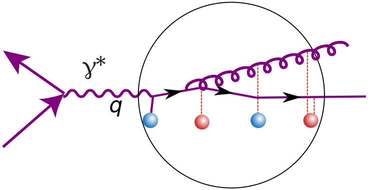
where the jet quenching parameter

$$\boxed{\hat{q}(1/x_\perp^2) = \frac{4\pi^2\alpha_s C_F}{N_c^2-1}\rho_0 x G(x, 1/x_\perp^2)}$$

Baier, Dokshitzer, Mueller, Peigne and Schiff, Nucl. Phys. B ***484****, 265 (1997).*

and the saturation momentum squared $Q_s^2 = 2\sqrt{R^2 - b^2}\hat{q}$.

After resumming Sudakov logs (radiation) and multiple scattering:



$$\frac{dN}{d^2b\,d^2k_\perp} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{-ik_\perp\cdot x_\perp} \rho\, xq_N\left(x, \frac{1}{x_\perp^2 + 1/Q^2}\right)$$

$$\times \int_0^L dz \exp\left[\underbrace{-\frac{1}{4}\hat{q}_t x_\perp^2 z}_{\text{medium-induced}} \underbrace{-\frac{\alpha_s C_F}{2\pi}\ln^2\left(Q^2 x_\perp^2\right)}_{\text{vacuum radiation}}\right]$$

where medium-induced double logs are included in $\hat{q}_t$.

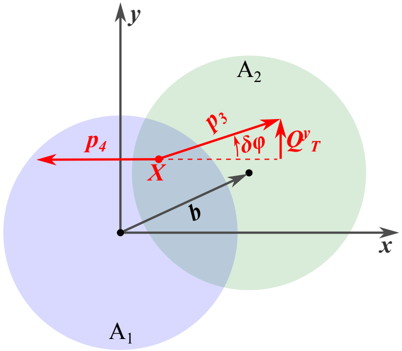
Mueller, BW, Xiao and Yuan, Phys. Rev. D **95**, no.3, 034007 (2017) [arXiv:1608.07339 [hep-ph]].

Here, we only studied leading log results (including also the BK evolution). See the talks by Jalilian-Marian, Caucal etc for summarizing recent progress.

Azimuthal decorrelation in AA

The focus of this talk: the first step toward verifying factorization in AA when both radiation and multiple scattering are include.

The observable: $Q \gg |Q_T^y| \gg \Lambda_{QCD}$



$$\frac{1}{p_T}\frac{d\sigma_{A_1A_2}}{d^2\mathbf{b}d\eta_3 d\eta_4 dp_T d\delta\varphi} \approx \frac{d\sigma_{A_1A_2}}{d^2\mathbf{b}d\eta_3 d\eta_4 dp_T dQ_T^y}$$

with $\delta\varphi = \arcsin(Q_T^y/|\mathbf{p}_3|)$, $\mathbf{Q}_T \equiv \mathbf{p}_3 + \mathbf{p}_4$, $Q = p_T \equiv |\mathbf{p}_4| \approx |\mathbf{p}_3|$.

The Feynman rules

The impact-parameter dependent cross section

After using the Glauber modelling of nuclei, one has

$$\frac{d\sigma}{d^2\mathbf{b}dO} = \int \prod_f [d\Gamma_{p_f}]\, \delta(O - O(\{p_f\}))$$
$$\times \prod_{i=1}^{A_1} \frac{1}{2P_1} \int d^2\mathbf{b}_i\, db_i^- \hat{\rho}_{A_1}(b_i^-, \mathbf{b}_i) \int \frac{dq_i^+ d^2\mathbf{q}_i}{(2\pi)^3} e^{\frac{i}{2} q_i^+ b_i^- - i\mathbf{q}_i\cdot\mathbf{b}_i}$$
$$\times \prod_{j=1}^{A_2} \frac{1}{2P_2} \int d^2\mathbf{b}'_j\, db_j'^+ \hat{\rho}_{A_2}(b_j'^+, \mathbf{b}'_j - \mathbf{b}) \int \frac{dq_j'^- d^2\mathbf{q}'_j}{(2\pi)^3} e^{\frac{i}{2} q_j'^- b_j'^+ - i\mathbf{q}'_j\cdot\mathbf{b}'_j}$$
$$\times \langle \{P_1 - q_i/2\}, \{P_2 - q'_j/2\} | \hat{S}^\dagger | \{p_f\} \rangle \langle \{p_f\} | \hat{S} | \{P_1 + q_i/2\}, \{P_2 + q'_j/2\} \rangle,$$

where $\hat{\rho}_{A_i} = \rho_{A_i}/A_i$ with $\rho_{A_i}(b^\pm, \mathbf{b})$ is the distribution of nucleons in nucleus i (usually with a Woods-Saxon functional form), the momenta of the constituent nucleons within the two nuclei are respectively given by $P_1^\mu = P_1^+ n_1^\mu/2$ and $P_2^\mu = P_2^- n_2^\mu/2$, with the two beam directions defined as $n_1^\mu = (1,0,0,1)$ and $n_2^\mu = (1,0,0,-1)$.

BW, JHEP **07** (2021), 002 [arXiv:2102.12916 [hep-ph]].

Expressing nucleon-nucleon scattering in terms of parton-level scattering

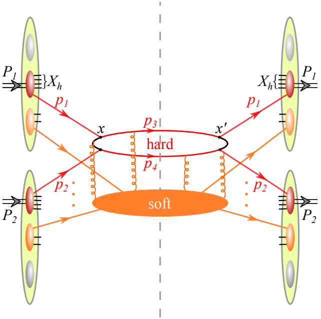
$$
\begin{aligned}
\frac{d\sigma}{d^2\mathbf{b}dO} = & \int \prod_f [d\Gamma_{p_f}]\, \delta(O - O(\{p_f\})) \\
& \times \sum_{\{a_i, b_j\}} \left(\prod_{i=1}^{A_1} \frac{1}{P_1^+} \int \frac{d\xi_i}{\xi_i} f_{a_i}(\xi_i) \right) \left(\prod_{j=1}^{A_2} \frac{1}{P_2^-} \int \frac{d\xi_j'}{\xi_j'} f_{b_j}(\xi_j') \right) \\
& \times \langle \{\xi_i P_1\}, \{\xi_j' P_2\} | \hat{S}^\dagger | \{p_f\} \rangle \langle \{p_f\} | \hat{S} | \{\xi_i P_1\}, \{\xi_j' P_2\} \rangle \\
& \otimes \left(\prod_{i=1}^{A_1} \hat{\rho}_{A_1}(X_i^-, \mathbf{X}_i) \right) \left(\prod_{j=1}^{A_2} \hat{\rho}_{A_2}(Y_j^+, \mathbf{Y}_j - \mathbf{b}) \right),
\end{aligned}
$$

where a_i and b_j iterate over all the parton species, and the operator $\otimes$ indicates that the incoming partons i and j enter the diagrams in the amplitude (the conjugate amplitude) at x_i (x_i') and y_j (y_j') respectively with $X_i = (x_i + x_i')/2$ and $Y_j = (y_j + y_j')/2$.

To check whether it factors at leading order in $s_{NN} \equiv P_1^+ P_2^-$ and nuclear size.

Néstor Armesto and Florian Cougoulic and BW, arXiv:2407.19243.

Expansion of Feynman diagrams



The uncorrelated nucleons are categorized into three groups:

1. the ones initiating the hard processes (red)
2. the ones participating the semi-hard (soft) process (orange)
3. spectators (gray)

We expand all the diagrams at large $Q = p_T$ and s_{NN} (that is, large x partons):

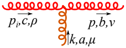
1. the offshell internal propagators (black lines) shrink into points, **denoted by** X.
2. leading terms in nuclear size: soft/Glauber gluons hooking on the external legs of the hard part

Gauge choice: the Feynman gauge

It is natural to use lightcone gauge in DIS but there are at least two different collinear directions in AA.

Feynman rules in eikonal limit:

$$\rightarrow -ig\not{p}_i D_F(p)\not{A} u_{p_i} = -2ig(p_i \cdot A)D_F(p)u_{p_i}$$

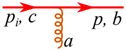


$$\rightarrow -gf^{abc}[2p_i \cdot A^a \epsilon^{\nu}(p) - A^a \cdot \epsilon(p)\ p_i^{\nu}]D_F(p)$$

with $D_F(p) \equiv \frac{i}{p^2+i\epsilon}$.

After using the ward identity:

$$= D_F(p),$$



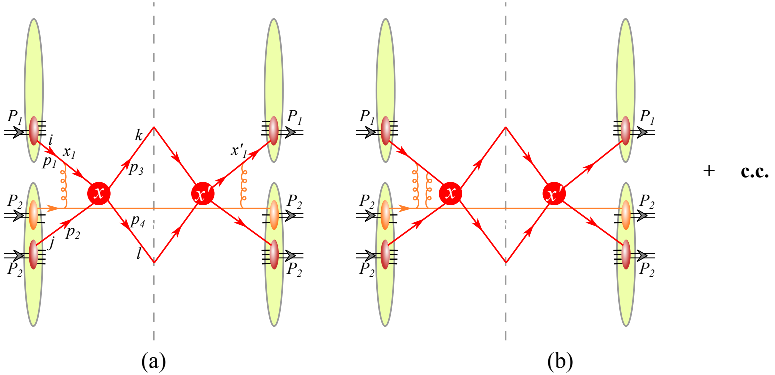
$$= -ig\hat{T}^a 2p_i \cdot A^a$$

where all collinear partons are represented by solid lines, and $\hat{T}^a$ stands for the color generator: $\hat{T}^a_{bc} = t^a_{bc}$ for quarks, $\hat{T}^a_{bc} = -t^a_{cb}$ for antiquarks, and $\hat{T}^a_{bc} = -if^{abc}$ for gluons.

The Drell-Yan process

Initial-state single scattering

All the single-scattering diagrams



plus those with nuclei 1 and 2 swapped. Diagrams with the Glauber gluon connecting two partons collinear to the same direction vanish in eikonal limit.

$$\frac{d\sigma_{A_1A_2\to l^+l^-}}{d^2\mathbf{b}d\eta_3 d\eta_4 dp_T d^2\mathbf{Q}_T} = 2\int d^4X\rho_{A_1}(X^-,\mathbf{X})\rho_{A_2}(X^+,\mathbf{X}-\mathbf{b})\sum_{ij}\frac{d\sigma^{(0)}_{ij\to l^+l^-}}{d\eta_3 d\eta_4 dp_T}$$

$$\times\int\frac{d^2\mathbf{x}}{(2\pi)^2}e^{-i\mathbf{x}\cdot\mathbf{Q}_T}\left[1-\frac{|\mathbf{x}|^2}{4}\int_{-\infty}^{X^+}dX_1^+\hat{q}_{i/A_2}(X_1^+,\mathbf{X}-\mathbf{b},|\mathbf{x}|)\right.$$

$$\left.-\frac{|\mathbf{x}|^2}{4}\int_{-\infty}^{X^-}dX_1^-\hat{q}_{j/A_1}(X_1^-,\mathbf{X},|\mathbf{x}|)\right].$$

More about $\hat{q}$:

$$\hat{q}_{j/A_i}(X^\pm,\mathbf{X},|\mathbf{x}|)=\frac{4\pi^2\alpha_s C_j}{N_c^2-1}\rho_{A_i}(X^\pm,\mathbf{X})xG(x,1/|\mathbf{x}|^2).$$

Here, xG is the TMD PDF at this order in the limit $x\to 0$

$$xG(x,1/|\mathbf{x}|^2)=\frac{\alpha_s C_F}{\pi}\ln\left(\frac{1}{\mu^2|\mathbf{x}|^2}\right)\int d\xi f_q(\xi,\mu).$$

Physical interpretation: Each collinear parton that enters the hard vertex absorbs a gluon with transverse momentum $p_T\sim\delta\phi Q$ from a nucleon moving in the opposite direction.

Resumming multiple scattering

Factorized multiple scattering due to the fact that diagrams with the Glauber gluon connecting two partons collinear to the same direction vanish.

In heavy nuclei, the summation of multiple scattering results can be substituted by the exponentiation of single scattering results, namely:

$$\frac{d\sigma_{A_1 A_2 \to l^+ l^-}}{d^2\mathbf{b}\, d\eta_3\, d\eta_4\, dp_T\, d^2\mathbf{Q}_T} = 2\int d^4X \rho_{A_1}(X^-, \mathbf{X})\rho_{A_2}(X^+, \mathbf{X}-\mathbf{b}) \sum_{ij} \frac{d\sigma^{(0)}_{ij\to l^+ l^-}}{d\eta_3\, d\eta_4\, dp_T}$$
$$\times \int \frac{d^2\mathbf{x}}{(2\pi)^2} e^{-i\mathbf{x}\cdot\mathbf{Q}_T - \frac{|\mathbf{x}|^2}{4}\int_{-\infty}^{X^+} dX_1^+ \hat{q}_{i/A_2}(X_1^+, \mathbf{X}-\mathbf{b}, |\mathbf{x}|)}$$
$$\times\, e^{-\frac{|\mathbf{x}|^2}{4}\int_{-\infty}^{X^-} dX_1^- \hat{q}_{j/A_1}(X_1^-, \mathbf{X}, |\mathbf{x}|)}.$$

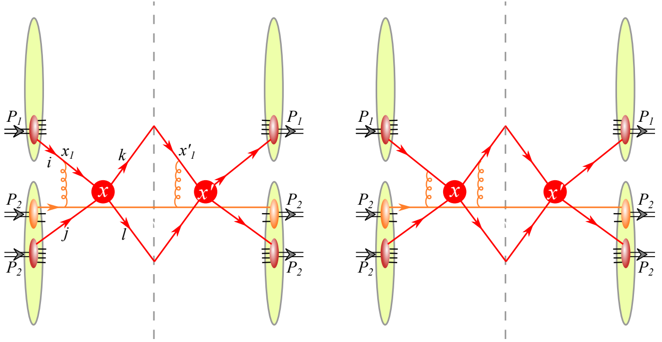
Recall in DIS

$$\frac{dN}{d^2b\, d^2Q_T} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{-iQ_T\cdot x_\perp} \rho_0 x q_N(x) \int_0^L dz\, e^{-\frac{1}{4}\hat{q} x_\perp^2 z}$$

Kovchegov and Mueller, Nucl. Phys. B **529**, 451 (1998).

The boson-jet process

Interference between single scattering



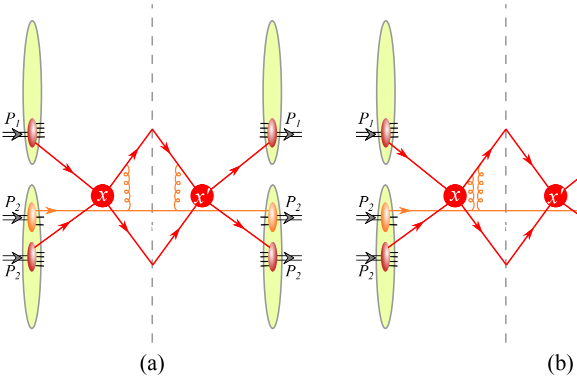
(a) (b)

+ **c.c.**

They vanish in high Q expansion.

Final-state single scattering

Only nonvanishing single-scattering diagrams besides initial-scattering



$+ \quad$ **c.c.**

plus those with nuclei 1 and 2 swapped.

Collecting single-scattering results from both initial- and final-states yields

$$\frac{d\sigma^{(1)}_{A_1A_2\to JV}}{d^2\mathbf{b}d\eta_3 d\eta_4 dp_T dQ_T^y} = -\frac{1}{2}\int d^4X \rho_{A_1}(X^-,\mathbf{X})\rho_{A_2}(X^+,\mathbf{X}-\mathbf{b})\int \frac{dy}{2\pi}e^{-iyQ_T^y}y^2$$

$$\times \sum_{ijk}\Big[\int_{-\infty}^{X^+} dX_1^+ \frac{d\sigma^{(0)}_{ij\to kV}}{d\eta_3 d\eta_4 dp_T}\hat{q}_{i/A_2}(X_1^+,\mathbf{X}-\mathbf{b},|y|)$$

$$+\int_{-\infty}^{X^-} dX_1^- \frac{d\sigma^{(0)}_{ij\to kV}}{d\eta_3 d\eta_4 dp_T}\hat{q}_{j/A_1}(X_1^-,\mathbf{X},|y|)$$

$$+\int_{X^+}^{\infty} dX_1^+ \frac{d\sigma^{(0)}_{ij\to kV}}{d\eta_3 d\eta_4 dp_T}\hat{q}_{k/A_2}(X_1^+,\mathbf{X}((X_1^+ - X^+)/n_3^+)-\mathbf{b},|y|)$$

$$+\int_{X^-}^{\infty} dX_1^- \frac{d\sigma^{(0)}_{ij\to kV}}{d\eta_3 d\eta_4 dp_T}\hat{q}_{k/A_1}(X_1^-,\mathbf{X}((X_1^- - X^-)/n_3^-),|y|)\Big].$$

The final-state broadening is determined by $\hat{q}$ along the jet trajectory!

Resumming multiple scattering

Iterating the above final-state single scattering as well as initial-state single scattering yields

$$\frac{d\sigma_{A_1A_2\to JV}}{d^2\mathbf{b}d\eta_3 d\eta_4 dp_T dQ_T^y} = \sum_{ijk} \frac{d\sigma^{(0)}_{ij\to kV}}{d\eta_3 d\eta_4 dp_T} \int dX^+ dX^- d^2\mathbf{X}$$

$$\times\, \rho_{A_1}(X^-,\mathbf{X})\, \rho_{A_2}(X^+,\mathbf{X}-\mathbf{b})$$

$$\times \int \frac{dy}{2\pi} e^{-iyQ_T^y} e^{-\frac{y^2}{4}\int_{-\infty}^{X^+} dX_1^+ \hat{q}_{i/A_2}(X_1^+,\mathbf{X}-\mathbf{b},|y|)}$$

$$\times\, e^{-\frac{y^2}{4}\int_{-\infty}^{X^-} dX_1^- \hat{q}_{j/A_1}(X_1^-,\mathbf{X},|y|)}$$

$$\times\, e^{-\frac{y^2}{4}\int_{X^+}^{\infty} dX_1^+ \hat{q}_{k/A_2}(X_1^+,\mathbf{X}((X_1^+-X^+)/n_3^+)-\mathbf{b},|y|)}$$

$$\times\, e^{-\frac{y^2}{4}\int_{X^-}^{\infty} dX_1^- \hat{q}_{k/A_1}(X_1^-,\mathbf{X}((X_1^--X^-)/n_3^-),|y|)}$$

Summary and Perspective

1. We derive the cross sections, including multiple scattering, for both the Drell-Yan and boson-jet processes in AA.

2. These cross sections appear similar to those in DIS or pA, with $\hat{q}$ or, equivalently, Q_s^2 involved in multiple directions.

3. They suggest that it may be worthwhile to explore the possibility of "seeing" evidence of parton saturation at midrapidity in AA.

4. However, it is expected that the Sudakov factor (from radiation) will make it difficult to extract information solely about multiple scattering (saturation).

5. For jet processes, the so-called cold nuclear effects discussed above only contribute partially to the observable.