Factorization of QCD jet cross section in Heavy-Ion collision at the lowest order

FC, collaboration with N. Armesto, and B. Wu

New jet quenching tools to explore equilibrium and non-equilibrium dynamics in heavy-ion collisions.

ECT* - February 12-16, 2024

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Cold nuclear effects on azimuthal decorrelation in Heavy-Ion collision

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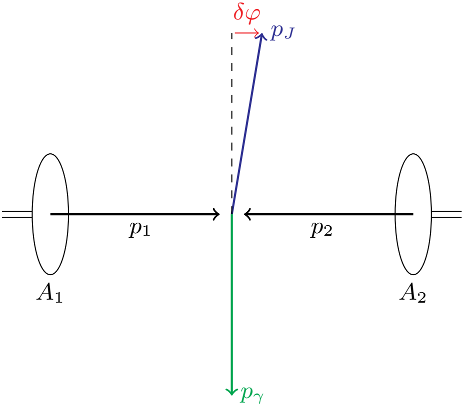
Initial setup

Regime of interest

- Large nuclei: $A_1, A_2 \gg 1$.
- Mid-rapidity back to back pair $\{\text{Jet} - \gamma\}$. Mostly transverse momenta $p_J \sim p_\gamma \sim Q$
- Observable: azimuthal decorrelation ($\Leftrightarrow$ Momentum imbalance) $\delta\varphi$
- Scaling $\delta\varphi \sim Q^y/Q \ll 1$, with Q^y semihard scale $Q^y \gg \Lambda_{QCD}$



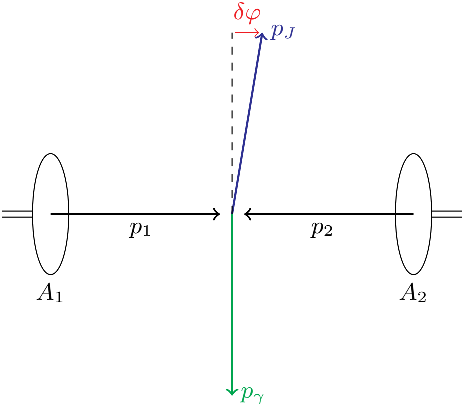
Initial setup

Goals:

- Prove to the best of our knowledge from first principle factorization for DY and jet-γ in AA collisions.
- Compute the leading order correction in α_S to the azimuthal decorrelation due to cold nuclear effects.
- Computed using single scattering, further resumed.

Result:

- Factorization of the hard process with the medium-modified initial state parton distribution and medium-modified jet function.



Outline

Part 1: Baseline

- Setup
- Localization of the hard process

Part 2: Medium implementation

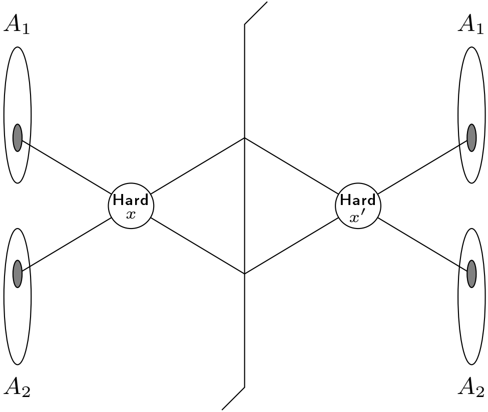
- Glauber gluons and implications

Part 3: Recovering a factorization formula

- Initial state effect
- Final state effect
- Interference terms

Part 1: Baseline

Baseline: Factorization of the bare process



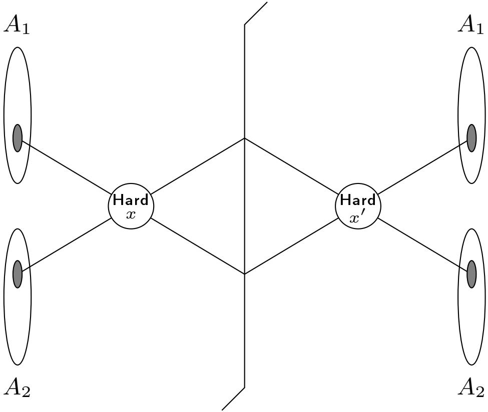
Setup:

- Working in coordinate space.
- Describe colliding nuclei states by introducing the Wigner function. For the plus moving A_1, and $q^+ \ll P^+$, we have

$$W_{A_1}(P, b) = \int \frac{dq^+ d^2\underline{q}}{(2\pi)^3 2P^+} e^{-\frac{i}{2}q^+ b^- + i\underline{q}\cdot\underline{b}} \times \langle P + q/2 | A_1 \rangle \langle A_1 | P - q/2 \rangle = \hat{\rho}_{A_1}(b^-, \underline{b}) 2(2\pi)^3 \delta^3(P - P_1)$$

  $\Rightarrow$ Introduce the color charge density $\hat{\rho}$.
- This is the McLerran-Venugopalan model. Nucleons are assumed uncorrelated, and partons within are recoilless classical sources of the gluon field.

Baseline: Factorization of the bare process



Observable:

- Hard process: inner propagators far off-shell
  $\Longrightarrow$ Those propagators shrink to points (wrt to any other separation involved)
- Sum over all possible nucleon yields the impact parameter dependent cross section for the observable $\mathcal{O}$
- Involve the parton distributions of nucleons within the nuclei, and the partonic cross section $\hat{\sigma}_{ij\to k\ell}$

$$\frac{d\sigma^{(0)}}{d^2\underline{b}d\mathcal{O}} = 2\int d^4X \rho_{A_1}(X^-, \underline{X})\rho_{A_2}(X^+, \underline{X}-\underline{b})\sum_{ij}\int d\xi_1 d\xi_2 f_i(\xi_1)f_j(\xi_2)\frac{d\hat{\sigma}_{ij\to k\ell}}{d\mathcal{O}} \tag{1}$$

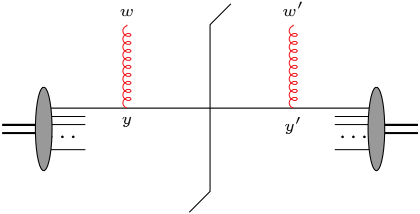
using $X = \frac{1}{2}(x+x')$

Part 2: Medium implementation

Medium Implementation: Glauber gluons

Add and extra scattering center / nucleon

Real diagram

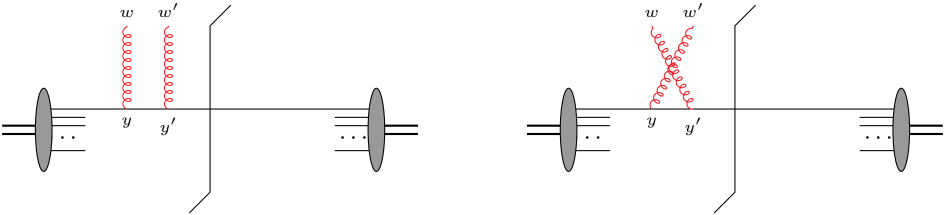


- Background field obtained following the MV model
- Sources: fast parton moving in the direction of either A_1 or A_2. Focus only on A_2 in this presentation
- Expectation value of the 2 points correlator $\langle A(w)A(w')\rangle$ in coordinate space, over all possible nucleon configurations
- Glauber gluon: propagator dominated by the transverse momenta $k^2 \longrightarrow -\underline{k}^2$

Features of interest:

- Integrate out the final state parton after emission of the red gluons.
  $\longrightarrow$ Sets the time at y to be the same as y'
- Glauber gluon are instantaneous:
  $\longrightarrow$ Sets the time at w to be the same as $w' \Longrightarrow$ **Locality w.r.t. time**
- Remains the dependence on the transverse separations.
  $\Longrightarrow$ Encoded by model dependent (dim-reg / IR cutoff / dipoles, ...) functions, which we denote by $F_1(\underline{w}-\underline{y})F_1(\underline{w}'-\underline{y}')$.

Virtual diagrams



Done many times before, some key points:

- See BDMPS-Z / GLV / ...
- Result similar to the real diagram
- Only two changes: (1) Relative sign wrt the real diagram, and (2) the transverse phase changes

Part 3: Recovering a factorization formula

Recovering a factorization formula: basic tools

Feynman propagator in coordinate space at high energy

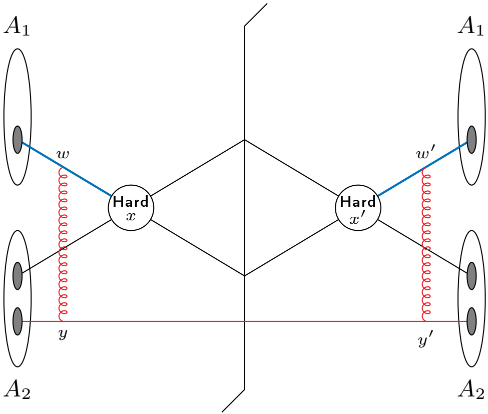
$$D_F(x) \longrightarrow \int \frac{dp^{n_j}}{2\pi}\frac{1}{2p^{n_j}} e^{-\frac{i}{n_i\cdot n_j}p^{n_j}x^{n_i}} \theta(x^{n_j}) \times \frac{n_i\cdot n_j}{4\pi i\ x^{n_j}} exp\left(\frac{i}{2}\frac{n_i\cdot n_j}{2}\frac{p^{n_j}}{x^{n_j}}\underline{x}_{ij}^2\right) \qquad (2)$$

using $g^{\mu\nu} = \frac{n_i^\mu n_j^\nu + n_j^\mu n_i^\nu}{n_i\cdot n_j} - g_{\perp ij}$ and $v^{n_i} \equiv v\cdot n_i$.

Remarks:

- For usual plus-minus movers: usual light cone coordinates.
- Starts being interesting when the mover are not parallel. Think of an initial parton in the e_z direction and a produced parton moving in the e_x direction.
  The transverse part is wrt the two directions n_i and n_j.
- In the high energy limit: Gaussian in transverse space becomes a Dirac delta.
- x^{n_j} plays the role of time.

Recovering a factorization formula: Initial state



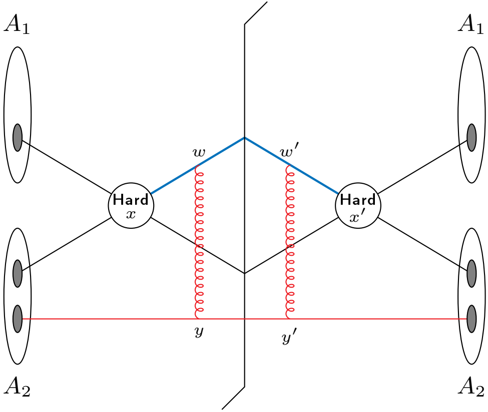
Real diagram

- Need to integrate over w and w' positions.
- Use the time ordering from the Feynman propagator:
  $(X - w)^+ > 0$ and $(X - w')^+ > 0$
- Average the bg fields $\langle A(w)A(w')\rangle$, use the locality in time of the 2pts function.

Iterating

- Recurssive use of the locality of the 2pts function and the time ordering in the Feynman propagator (eikonal limit).
- Building up a Wilson line along the plus-direction.

Alternatively Recast into a medium-modified initial distribution



Metric

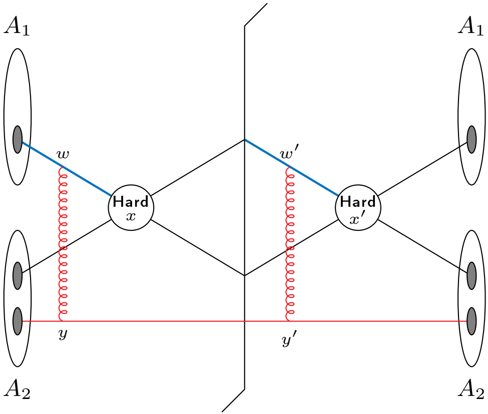
- Use $n_i = n_3$, in the plane transverse to the beam direction.
- For the interaction with the minus moving nucleon, use $n_j = n_1$
- Feynman propagator is proportional to $\theta(x^+)$. With this choice, we use the same time as the previous case.

Real diagram

- Need to integrate over w and w' positions.
- From Feynman propagators: $w^+ - X^+ > 0$ and $w'^+ - X^+ > 0$
- Use the properties of the bg field average, and iterate to build-up a Wilson line in the n_3 direction.

Alternatively Recast into a medium-modified jet function:

Recovering a factorization formula: Interference



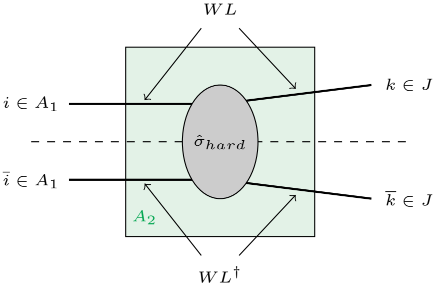
Short answer

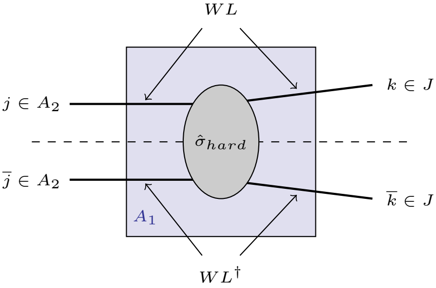
- Using the same metric, $n_i = n_3$ and $n_j = n_1$, same time v^+
- Integrate over w and w'
- From the propagators $D_F(X - w)$, $\Rightarrow$ we have $X^+ > w^+$
- From The propagator $D_F(w' - X)$, $\Rightarrow$ we have $w'^+ > X^+$
- Perform the average over the bg fields. It sets $w^+ = w'^+ \longrightarrow$ No support

Due to the lack of support, interference diagrams vanish

Summary and Prospects

Summary: consider $A_1 A_2 \to J + \gamma$. *Schematic result*





Alternatively

- Initial distribution of parton $i \in A_1$ modified by the cold medium A_2
- Initial distribution of parton $j \in A_2$ modified by the cold medium A_1
- Jet function of parton k is modified by cold medium A_1 and cold medium A_2

One very last equation:

$$\frac{d\sigma^{(1)}_{A_1A_2\to J\gamma}}{d^2\underline{b}\,d\eta_3 d\eta_4 dp_T dQ_T^y} = \frac{-1}{2}\int d^4X \rho_{A_1}(X^-,\underline{X})\rho_{A_2}(X^+,\underline{X}-\underline{b})\int \frac{dy}{2\pi}e^{-iyQ_T^y}y^2$$
$$\times\sum_{ijk}\Bigg[\int^{X^+} dW^+ \left.\frac{d\sigma^{(0)}_{ij\to k\gamma}}{d\eta_3 d\eta_4 dp_T}\right|_{X^+-W^+} \hat{q}_{i/A_2}(W^+,\underline{X}-\underline{b},|y|)$$
$$+\int^{X^-} dW^- \left.\frac{d\sigma^{(0)}_{ij\to k\gamma}}{d\eta_3 d\eta_4 dp_T}\right|_{X^--W^-} \hat{q}_{j/A_1}(W^+,\underline{X},|y|)'$$
$$+\int_{X^+} dW^+ \left.\frac{d\sigma^{(0)}_{ij\to k\gamma}}{d\eta_3 d\eta_4 dp_T}\right|_{W^+-X^+} \hat{q}_{k/A_2}(W^+,\underline{X}\frac{W^+-X^+}{n_3^+},|y|)$$
$$+\int_{X^-} dW^- \left.\frac{d\sigma^{(0)}_{ij\to k\gamma}}{d\eta_3 d\eta_4 dp_T}\right|_{W^--X^-} \hat{q}_{k/A_1}(W^-,\underline{X}\frac{W^--X^-}{n_3^-},|y|)\Bigg]$$

Prospects: - higher order in α_S (add more gluons for more fun!)

- Introduce radiation. Where is the Sudakov? What about the medium modification?
- Finding small-x evolution?
- Can we distinguish? Is there overlap?

Some random diagrams: