COHERENCE EFFECTS BETWEEN INITIAL AND FINAL STATE RADIATION IN A DENSE QCD MEDIUM

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arXiv:1308.2186
Motivation

A hot and dense deconfined coloured medium (QGP) is produced in Ultrarelativistic Heavy Ion Collisions

⇒ Nuclear modifications to the fragmentation functions and PDFs
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A hot and dense deconfined coloured medium (QGP) is produced in Ultrarelativistic Heavy Ion Collisions

⇒ Nuclear modifications to the fragmentation functions and PDFs

Observables in HI Collisions are related to the properties of the QGP

⇒ Using pA to constrain nuclear PDFs

⇒ Assume no final state interactions. But....
Possible evidence of final state interactions in pA
⇒ Flow harmonics comparable to AA
Possible evidence of final state interactions in pA

⇒ Flow harmonics comparable to AA

QCD medium of finite size leads to color decoherence effects

⇒ Modifications to the hadronic outcome subsist for large pT

⇒ Jet quenching effects might be seen in pA

See K. Tywoniuk’s talk
Medium of finite size
Collinear Factorization

\[ BDMPS \Rightarrow Q^2 \]

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Medium of finite size
Collinear Factorization

\[ BDMPS \Rightarrow \]

\( Q^2 \)

QGP

\( Q_s \)

Shockwave
\( k_T \) factorization
Hybrid formalism

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“Coherence effects between Initial and Final SR in a dense QCD medium”
Medium of finite size
Collinear Factorization

$BDMPS \Rightarrow$

How is the vacuum coherence pattern get affected?
Do we have: Collinear factorization?
$k_T$ Factorization?
Something else?
Color coherence in a DIS-like process

\[ \omega \frac{dN}{d^3k} = \frac{\alpha_s C_F}{(2\pi)^2 \omega^2} \left[ Q_b^2 R_b + Q_c^2 R_c + 2 Q_b \cdot Q_c J \right] \]

\[ = \frac{\alpha_s C_F}{(2\pi)^2 \omega^2} \left[ Q_b^2 (R_b - J) + Q_c^2 (R_c - J) + Q_a J \right] \]

Singlet \( Q_a = 0 \)

Octet \( Q_a \neq 0 \)

Coherent spectrum

\[ \langle dN_i \rangle_\phi = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta_i}{\theta_i} \Theta(\theta_{qq} - \theta_i) \]

Collinear and soft divergence
Suppression of soft gluons
A natural question

What happens in a QCD medium?
First steps: antenna inside a QCD medium

\[ Q_{\text{hard}} = \max \left( r_{\perp}^{-1}, Q_s \right) \]

\[ Q_s^2 = \hat{q}L, \quad r_{\perp} = \theta_{q\bar{q}}L \]

Armesto, Mehtar-Tani, Salgado, Tywoniuk, Iancu, Casalderrey-Solana
Medium modifications to the initial and final state interference pattern

N. Armesto, Hao Ma, M. Martinez, Yacine Mehtar-Tani, C. Salgado

Dilute regime: PLB 717 (2012) 280-286

Dense regime: 1308.2186 ⇒ In this talk!!!

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GOALS

✯ Study another configuration relevant to HI collisions
✯ Playground to investigate medium modifications to the Initial State Radiation
Classical Yang-Mills Eqs. I

Evolution of the gauge field:
\[
[D_\mu, F^{\mu\nu}] = \mathcal{J}^\nu
\]

Color charge conservation:
\[
[D_\mu, J^\mu] = 0
\]
Classical Yang-Mills Eqs. I

Evolution of the gauge field:
\[ [D_\mu, F^{\mu\nu}] = J^\nu \]

Color charge conservation:
\[ [D_\mu, J^\mu] = 0 \]

Linearizing around a background field:
\[ A^\mu = A^\mu_{med} + a^\mu \]

\[ \square_x a^i - 2ig [A^-_{med}, \partial_- a^i] = J^i - \partial^i \left( \frac{J^+}{\partial_-} \right) \]

LC gauge
Classical Yang-Mills Eqs. I

Evolution of the gauge field:
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\[ \Box_x a^i - 2ig [A^-_{med}, \partial_- a^i] = J^i - \partial^i \left( \frac{J_+}{\partial_-} \right) \]

LC gauge

Reduction formula:
\[ M_\lambda^a = \lim_{k^2 \to 0} \int d^4x e^{ik \cdot x} \Box_x A^a_\mu(x) \epsilon^\mu_\lambda(\vec{k}) \]
Evolution of the gauge field: \[ [D_\mu, F^{\mu\nu}] = \mathcal{J}^\nu \]

Color charge conservation: \[ [D_\mu, \mathcal{J}^\mu] = 0 \]

Linearizing around a background field: \[ A^\mu = A_{med}^\mu + a^\mu \]

\[ \Box_x a^i - 2ig [A_{med}^-, \partial_- a^i] = \mathcal{J}^i - \partial^i \left( \frac{\mathcal{J}^+}{\partial_-} \right) \]

LC gauge

Reduction formula:

\[ \mathcal{M}_\lambda^a = \lim_{k^2 \to 0} \int d^4 x e^{ik \cdot x} \Box_x A_\mu^a(x) \epsilon^\mu_\lambda(\vec{k}) \]

Gluon spectrum:

\[ (2\pi)^3 2k^+ \frac{dN}{d^3 k} = \sum_{\lambda=1,2} |\mathcal{M}_\lambda^a(\vec{k})|^2 \]
Eikonal parton in a background field:

\[ \mathcal{J}^\mu(x)_a = g v^\mu U^{ab}(x^+, 0) \delta^3(\vec{x} - \vec{v}t) \theta(t) Q_b \]

\[ U^{ab}(x^+, y^+) = \mathcal{P} \exp \left[ i g \int_{y^+}^{x^+} dz^+ A^{-}_{med}(z^+, r(z^+)) \right]^{ab} \]

Soft gluon follows a non-eikonal trajectory

\[ G_{ab}(x^+, x; y^+, y|k^+) = \int_{r(y^+)=y}^{r(x^+)=x} Dr \exp \left( i \frac{k^+}{2} \int_{y^+}^{x^+} dz \dot{r}^2(z) \right) U_{ab}(x^+, y^+) \]
Modeling the medium

Medium is described as a classical background field:

\[-\partial_x^2 A_{med}^-(x^+, x) = \rho(x^+, x)\]

The distribution of color charges is considered to be a Gaussian noise:

\[
\langle A_{med}^{a,-}(x^+, q) A_{med}^{b,-}(x'^+, q') \rangle = \delta^{ab} n(x^+) \delta(x^+ - x'^+) \delta^{(2)}(q - q') \mathcal{V}^2(q)
\]

\[
\lambda_{mfp} \gg m_D^{-1}
\]

\[
\mathcal{V}^2(q) = \frac{m_D^2}{(2\pi)^2(q^2 + m_D^2)^2}
\]

Gluon spectrum

BDMPS-Z + vacuum
Gluon spectrum

BDMPS-Z + vacuum

P_T broadening of ISR
Gluon spectrum

BDMPS-Z + vacuum

Interferences in the medium: New!!

P_T broadening of ISR

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Medium induced radiation is a two step process

- Quantum emission + classical broadening
- Scales with the length of the medium
Pt broadening of ISR is a two step process:

- **Collinear Emission** + classical broadening
- **Reshuffling of the momentum of the gluon emissions**

\[ \mathcal{P}(k, \xi) = \frac{4\pi}{\hat{q}\xi} e^{-\frac{k^2}{\hat{q}\xi}} \]

\[ \sim \int \frac{d^2k'}{(2\pi)^2} \mathcal{P}(k' - \bar{\kappa}, L^+) \]

\[ \sim Q_s = \hat{q}L \]

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Interferences

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Interferences

Transverse size of the Quark-gluon system

• If hard scattering is the largest scale:
  $\Rightarrow$ Insensitive to the medium

• If typical medium induced momentum is the largest scale
  $\Rightarrow$ Medium is able to resolve the qg system
Interferences

The Color correlation of the Quark-gluon system is measured by

\[ \mathcal{K}(x^+, x; y^+, y|x^+) = \int_{r(y^+)=y}^x \mathcal{D}r \exp \left[ \int_{y^+}^{x^+} d\xi \left( i \frac{k^+}{2} \dot{r}^2(\xi) - \frac{1}{2} n(\xi)\sigma(r(\xi)) \right) \right] \]

- Describes the Brownian motion of the gluon
- Harmonic oscillator approximation: \( n\sigma(r) \approx \hat{q}r^2 \)
- Two extreme limits
  - High Energy Limit (Shockwave) \( \tau_f \gg L \)
  - "Infinite" medium length \( \tau_f \ll L \)
Gluon spectrum: High Energy limit

- Medium acts as a unique scattering center
- Interferences are suppressed if $k < Q_s$
- Vacuum color coherence is reestablished for $k > Q_s$
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Medium acts as a unique scattering center
Interferences are suppressed if $k < Q_s$
Vacuum color coherence is reestablished for $k > Q_s$

$$\theta_{max} = \frac{Q_s}{\omega}$$

Geometrical Separation
Gluon spectrum: “Infinite” medium limit

- Interferences play a role at early-times
- Gluon loses vacuum coherence
  ⇒ Open phase space at large angle emissions up to \( \theta_{max} = \frac{Q_s}{\omega} \)
- Typical “medium induced” gluon momentum \( \sim \, Q_s \approx \hat{q}L \)
We want:

⇒ Include finite target size effects !!!!
⇒ Study color decoherence in pA !!!!
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⇒ Study color decoherence in pA !!!!

• Projectile described by QCD parton model
We want:

⇒ Include finite target size effects !!!!
⇒ Study color decoherence in pA !!!!

- Projectile described by QCD parton model
- Target described by a gaussian distr. of color charges.
We want:

⇒ Include finite target size effects !!!!
⇒ Study color decoherence in pA !!!!

- Projectile described by QCD parton model
- Target described by a gaussian distr. of color charges.
- Emitted gluon follows a non-eikonal trajectory.

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)
pA case

Factorized formula:

\[
\frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{y,z,\bar{y},\bar{z},y^+,\bar{y}^+} e^{-ik \cdot (z-\bar{z})} \left( \frac{(\bar{z} - \bar{y}) \cdot (z - y)}{(\bar{z} - \bar{y})^2 (z - y)^2} \right)\]

Probability to emit a soft gluon

\[
\left\{ \begin{array}{l}
\tilde{\delta}_0 \int_{\bar{z}'} e^{-ik \cdot (\bar{z} - \bar{z}')} \tilde{G}^\dagger (L^+, \bar{z}'; \bar{y}^+, \bar{z}) \\
- \mathcal{U}^\dagger (\bar{y}^+, 0, \bar{y}) \left[ \tilde{\delta}_{L^+} - \frac{1}{ik^+} \int_{\bar{z}'} e^{-ik \cdot (z - z')} \tilde{\partial} \bar{z} \tilde{G}^\dagger (L^+, \bar{z}'; \bar{y}^+, \bar{z}) \right] \end{array} \right\}^{bd}
\]

\[
\left\{ \begin{array}{l}
\delta_0 \int_{z'} e^{ik \cdot (z - z')} G(L^+, z'; y^+, z) \\
- \left[ \delta_{L^+} + \frac{1}{ik^+} \int_{z'} e^{ik \cdot (z - z')} \tilde{\partial} z G(L^+, z'; y^+, z) \right] \mathcal{U}(y^+, 0, y) \end{array} \right\}^{dc}
\]

Scattering probability of the partonic system

\[\langle \rho^b(\bar{y}) \rho^c(y) \rangle\]

Projectile distribution

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)
\[
\frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{y,z,y,z,y^+,y^+} e^{-ik \cdot (z-z')} \frac{(\bar{z} - \bar{y}) \cdot (z - y)}{(\bar{z} - \bar{y})^2 (z - y)^2}
\]

**pA case**

**Factorized formula:**

Finite medium size corrections + Color decoherence effects

\[
\delta_0 \int_{\bar{z}'} e^{-ik \cdot (\bar{z} - \bar{z}')} \mathcal{G}^\dagger(L^+, \bar{z}'; y^+, \bar{z}) - \mathcal{U}^\dagger(y^+, 0, \bar{y}) \left[ \delta_{L+} - \frac{1}{ik^+} \int_{\bar{z}'} e^{-ik \cdot (\bar{z} - \bar{z}')} \tilde{\partial} \mathcal{G}^\dagger(L^+, \bar{z}'; y^+, \bar{z}) \right]
\]

\[
\delta_0 \int_{\bar{z}'} e^{ik \cdot (z - z')} \mathcal{G}(L^+, z'; y^+, z) - \left[ \delta_{L+} + \frac{1}{ik^+} \int_{\bar{z}'} e^{ik \cdot (z - z')} \tilde{\partial} \mathcal{G}(L^+, z'; y^+, z) \right] \mathcal{U}(y^+, 0, y)
\]

Probability to emit a soft gluon

Scattering probability of the partonic system

**Non-eikonal corrections!!!**

**Projectile distribution**

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)
Factorized formula:

$$\omega \frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{y,z,\bar{y},z,y^+,\bar{y}^+} e^{-ik \cdot (z-\bar{z})} \frac{(\bar{z} - \bar{y}) \cdot (z - y)}{\bar{z} - \bar{y})^2 (z - y)^2}$$

Finite medium size corrections + Color decoherence effects

Probability to emit a soft gluon

Non-eikonal corrections!!

Scattering probability of the partonic system

Finite length Corrections!!

Projectile distribution

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)
\[ \omega \frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{y,z,\bar{y},\bar{z}} e^{ik \cdot (\bar{z}-z)} \frac{(\bar{z}-\bar{y}) \cdot (z-y)}{(\bar{z}-\bar{y})^2(z-y)^2} \]

\[ \text{Tr. } \left[ U_{\bar{z}}^\dagger U_z + U_{\bar{y}}^\dagger U_y - U_{\bar{z}}^\dagger U_y - U_{\bar{y}}^\dagger U_z \right] \langle \rho^a (\bar{y}) \rho^a (y) \rangle \]

This equation leads to the Hybrid Formalism

See T. Altinoluk and A. Kovner; PRD83 (2011) 105004

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)
pA case

High Energy limit $\Rightarrow k_T$ factorized formula

\[ \omega \frac{dN}{d^3k} \sim \frac{g^2}{\pi^2} \int_{y,z,\bar{y},\bar{z}} e^{i\mathbf{k} \cdot (\bar{z} - z)} \frac{(\bar{z} - \bar{y}) \cdot (z - y)}{(\bar{z} - \bar{y})^2 (z - y)^2} \]

\[ \text{Tr.} \left[ U_{\bar{z}z}^\dagger U_{\bar{z}z} + U_{\bar{y}y}^\dagger U_{\bar{y}y} - U_{\bar{z}y}^\dagger U_{\bar{y}z} - U_{\bar{y}z}^\dagger U_{\bar{y}y} \right] \langle \rho^a(\bar{y}) \rho^a(y) \rangle \]

This equation leads to the Hybrid Formalism
See T. Altinoluk and A. Kovner; PRD83 (2011) 105004

To do list (Keep tuned !!!!)
- Determine the dominant logarithmic behavior:
  $\Rightarrow$ Identify the "medium" induced elastic and inelastic terms.
- Make contact and generalize hybrid formalism.

Work in progress (Altinoluk, Armesto, Beuf, Martinez, Salgado)
Conclusions

• Interference pattern between the initial and final SR is indeed affected in the presence of a QCD medium.
• We observe a partial color decoherence between both emitters
  ⇒ Opening of phase space for large angle emissions
• We can generalize this setup for pA (work in progress)
  ⇒ phenomenological consequences at LHC (keep tuned!!!)
BACKUP SLIDES
Correlators

Quark-gluon dipole

\[
\frac{1}{N_c^2 - 1} \langle \mathcal{G}(x^+, x; y^+, y) \mathcal{U}^\dagger(x^+, y^+) \rangle = \mathcal{K}(x^+, x; y^+, y|k^+)
\]

\[
\mathcal{K}(x^+, x; y^+, y|k^+) = \int_{r(y^+)=y}^{r(x^+)=x} \mathcal{D}r \exp \left[ \int_{y^+}^{x^+} d\xi \left( \frac{i k^+}{2} \mathbf{r}^2(\xi) - \frac{1}{2} n(\xi) \sigma(\mathbf{r}(\xi)) \right) \right]
\]

Gluon dipole

\[
\int dx \, dx' \, e^{i \mathbf{k} \cdot (\mathbf{x} - \mathbf{x}')} \frac{1}{N_c^2 - 1} \langle \mathcal{G}(x^+, x; y^+, y) \mathcal{G}^\dagger(x^+, y^+) \rangle = S(x^+, y^+, x - y)
\]

\[
S(x^+, y^+; x - y) = \exp \left[ -\frac{1}{2} \int_{y^+}^{x^+} d\xi \, n(\xi) \sigma(\mathbf{x} - \mathbf{y}) \right]
\]

Dipole cross section

\[
\sigma(r) = \int \frac{d^2 \mathbf{q}}{(2\pi)^2} V(\mathbf{q}) \left[ 1 - \cos(\mathbf{r} \cdot \mathbf{q}) \right]
\]
Scattering amplitude from CYM Eqs.

\[
\mathcal{M}_{\lambda,\text{in}}(\vec{k}) = \frac{g}{k^+} \int d^2 x e^{i(k^+ - k : x)} \int_0^{L^+} dy^+ e^{ik^+ u^- y^+} \\
\times \epsilon_\lambda \cdot (i \partial_y + k^+ u) \mathcal{G}_{ab}(L^+, x, y^+, y = u y^+ | k^+) \mathcal{U}_{bc}(y^+, 0) Q_{c}^{\text{out}}
\]

\[
\mathcal{M}_{\lambda,\text{out}}(\vec{k}) = -2i \frac{\epsilon_\lambda \cdot \vec{k}}{\vec{k}^2} e^{i(k \cdot u) L^+} \mathcal{U}_{ab}(L^+, 0) Q_{c}^{\text{out}},
\]

Incoming parton

\[
\mathcal{M}_{\lambda,\text{bef}}(\vec{k}) = \frac{g}{k^+} \int_{x^+ = \infty} d^2 x e^{i(k^- - x^+ - k : x)} \int_0^{L^-} dy^+ e^{ik^+ u^- y^+} \\
\times \epsilon_\lambda \cdot (i \partial_y + k^+ u) \mathcal{G}_{ab}(x^+, x, y^+, y = u y^+ | k^+) Q_{b}^{\text{in}}
\]

Outcoming parton

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Leading logs and AO

\[ \kappa^2 < \delta k^2 \quad \delta k^2 \equiv Q^2 \]

\[ \omega \frac{dN}{d\omega d\kappa^2} = \frac{1}{\kappa^2} \quad \text{(DGLAP)} \]

\[ \omega \frac{dN}{d\omega} = \int_{Q_0^2}^{\delta k^2} \frac{d\kappa^2}{\kappa^2} = \log \left( \frac{\delta k^2}{Q_0^2} \right) \sim \log \left( \frac{Q^2}{Q_0^2} \right) \quad \text{L. L.} \]

\[ N \propto \int_{Q_0^2}^{Q^2} \omega \frac{dN}{d\omega} = \frac{1}{2} \left[ \log \left( \frac{Q^2}{Q_0^2} \right) \right]^2 \quad \text{D. L. L.} \]
Jets in HIC @ LHC

(i) Suppression of high-\(p_T\) hadrons

(ii) Soft large angle emissions

(iii) Significant dijet asymmetry

(iv) Vacuum-like fragmentation function

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]

\[ \Delta \phi > \pi/2 \]

\[ \xi = \ln(p_{T,\text{jet}}/p_{T,\text{track}}) \]

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