q / $\bar{q}$ Correlations in Heavy-Light Ion Collisions

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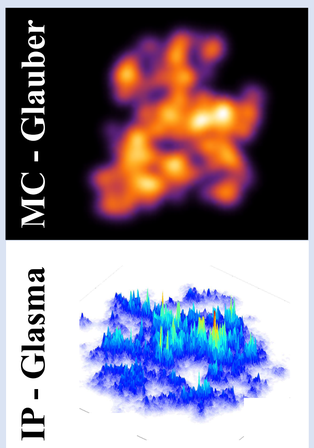
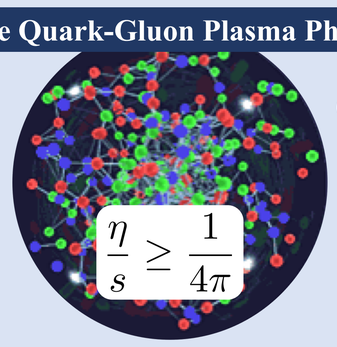


Introduction

- **Initial-state correlations** drive particle production
- **Sub-nucleonic QCD fluctuations** can have significant effects [1]
- Predominantly fluctuations of the **energy density**

The Quark-Gluon Plasma Phase

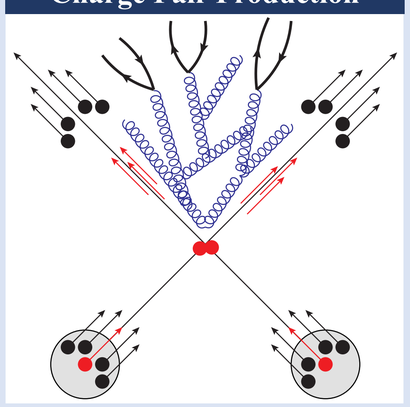


Energy Conservation $\partial_\mu T^{\mu\nu} = 0$

Charge Conservation $\partial_\mu J^\mu = 0$

- **Conserved charges** also propagate in QGP
- Created by gluon **pair production**
- How do their **initial correlations** affect particle production?

Charge Pair Production



Formalism

- Compute **spatial correlations among q , $\bar{q}$**

$$\mathcal{C}_{ij} \approx \frac{1}{\sigma_{inel}} \left[k_1^+ k_2^+ \frac{d\sigma^{ij}}{d^2B_1\, dk_1^+\, d^2B_2\, dk_2^+} \right]$$

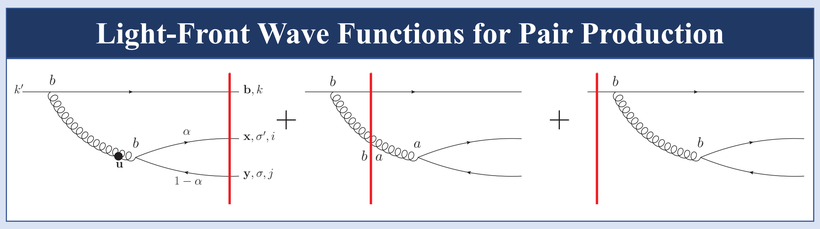
- **CGC** formalism in "**heavy / light**" regime [2]

$$\alpha_s^2 A^{1/3} \sim 1 \qquad \text{“Semi-dilute / dense”:}$$

$$\alpha_s \ll \alpha_s^2 a^{1/3} \ll 1 \qquad {}^3\text{He + Au, Cu + Au, etc.}$$

$$Q_s^2 \propto \alpha_s^2 A^{1/3} \qquad \textbf{Saturation momentum}$$

Light-Front Wave Functions for Pair Production

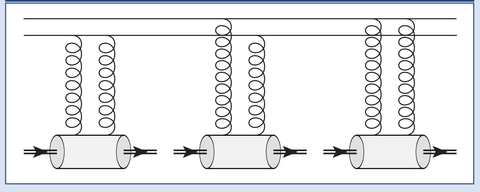


- Quark pair production is described by **wave functions** in **light-front perturbation theory** [3]

➢ **Instantaneous scattering** at $t = 0$

- **High-energy scattering** of partons occurs via **Wilson line** color rotations

Quasi-Classical Scattering



➢ **Quasi-classical** (Gaussian) limit

$$V_{\boldsymbol{x}} \equiv \mathcal{P} \exp\left[ig \int dx^+ A^-(x^+, 0^-, \boldsymbol{x}) \right]$$

- Dynamics via **color multipole** operators:

Dipole $\hat{D}_2(\boldsymbol{x}, \boldsymbol{y}) \equiv \frac{1}{N_c} \mathrm{tr}_C \left[V_{\boldsymbol{x}} V_{\boldsymbol{y}}^\dagger \right]$

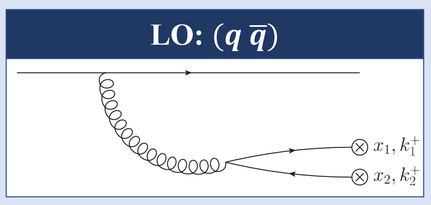
Quadrupole $\hat{D}_4(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}, \boldsymbol{w}) \equiv \frac{1}{N_c} \mathrm{tr}_C \left[V_{\boldsymbol{x}} V_{\boldsymbol{y}}^\dagger\, V_{\boldsymbol{z}} V_{\boldsymbol{w}}^\dagger \right]$

Single-Pair Production

- At **LO**: quark pair production from **one soft gluon**

➢ $(\boldsymbol{q}\, \bar{\boldsymbol{q}})$ only

LO: $(q\, \bar{q})$



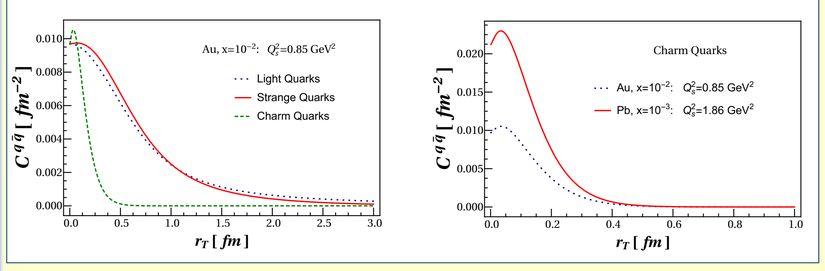
- Correl. fn. **normalized** by **gluon production**

Color dipoles (GBW model [4], large-Nc approx)

$$\mathcal{C}_{q\bar{q}}(\boldsymbol{r}, \alpha) = \frac{\alpha_s}{8\pi^2} m^2 \left(1 - e^{-\frac{1}{4}[\alpha^2 + (1-\alpha)^2] r_T^2 Q_s^2}\right) \left[\left(\alpha^2 + (1-\alpha)^2\right) K_1^2(mr_T) + K_0^2(mr_T) \right]$$

Massive quark splitting **wave functions**

$q\, \bar{q}$ Correlation Function



Range is controlled by the **quark mass**

Strength is controlled by $\boldsymbol{Q_s}$

- Quarks carry fractional **baryon number** charge

➢ LO contribution to **baryon number correlations**

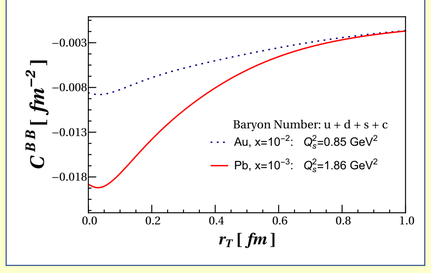
$$\mathcal{B} \equiv \frac{1}{3} \sum_f \left(n^{q_f} - n^{\bar{q}_f} \right)$$

$$\mathcal{C}_{\mathcal{B}\mathcal{B}}(\boldsymbol{r}) = -\frac{1}{9} \sum_f \left(\mathcal{C}_{q_f \bar{q}_f}(\boldsymbol{r}) + \mathcal{C}_{q_f \bar{q}_f}(-\boldsymbol{r}) \right)$$

Negative value

Anticorrelation due to **opposite charge** nearby

Baryon Number Correlations



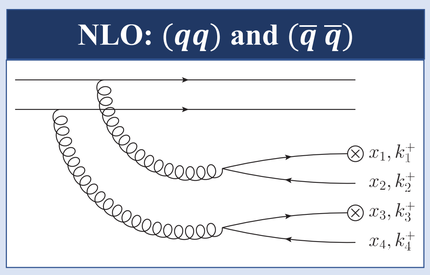
Double-Pair Production

- At **NLO**: two pairs are produced

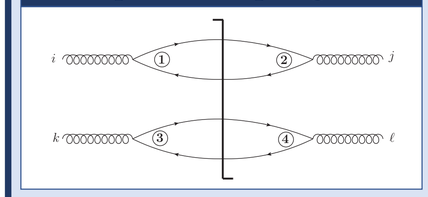
➢ $(\boldsymbol{qq})$ and $(\bar{\boldsymbol{q}}\, \bar{\boldsymbol{q}})$

➢ $(q\, \bar{q})$ at $\boldsymbol{r_T \gg \frac{1}{m}}$

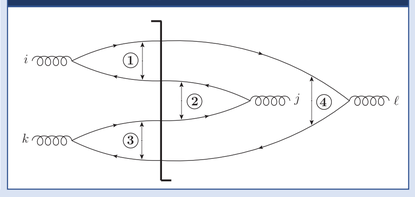
NLO: (qq) and $(\bar{q}\, \bar{q})$



Separated Topologies



Entangled Topologies



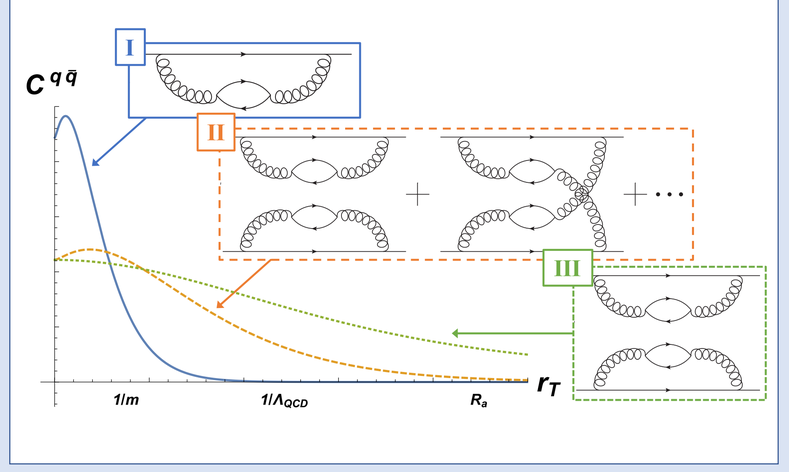
Long range correlations

Range limited to $\frac{1}{m}$

- **Fermi statistics** leads to **negative** contributions from quark entanglement (**Pauli blocking**) [5]

Regions	$\mathcal{C}_{q\bar{q}}$	$\mathcal{C}_{qq}$, $\mathcal{C}_{\bar{q}\bar{q}}$
$r_T \ll \frac{1}{m}$	Single-Pair	Double-Pair: **Separated** + **Entangled**
$\frac{1}{m} \ll r_T \ll \frac{1}{\Lambda_{QCD}}$		Double-Pair: **Separated Only** **Full CGC** dynamical correlations
$\frac{1}{\Lambda_{QCD}} \ll r_T$		Double-Pair: **Separated only** **Nonperturbative correlations only**

Qualitative Features: Single- and Double-Pair Regimes



Conclusions

- We calculated the $(q\, \bar{q})$ spatial correlation functions for **single-pair production**
- We outlined the **mechanisms** and **length scales** associated with **double-pair production**
- This is one step toward a **numerical package for initializing conserved charges** in heavy ion collisions.

$\mathcal{C}_{q\bar{q}}$: The **range** is controlled by the **quark mass**
The **strength** is controlled by the **saturation scale**

$\mathcal{C}_{qq}$, $\mathcal{C}_{\bar{q}\bar{q}}$: **Entangled** vs. **Separated** topologies
Three distinct regions based on $\frac{1}{m}$ and Λ_{QCD}

References

[1] B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. **108** (2012)

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[3] J. P. Blaizot , F. Gelis, R. Venugopalan, Nucl. Phys. **A743** (2004), Y. Kovchegov, K. Tuchin, Phys. Rev. **D74** (2006)

[4] K. J. Golec-Biernat and M. Wusthoff, Phys. Rev. **D59** (1998)

[5] T. Altinoluk, N. Armesto, G. Beuf, A. Kovner, M. Lublinsky, Phys. Rev. **D95** (2017)