Two particle correlations in pA collisions from the CGC

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based on [Altinoluk, Armesto, Kovner, Lublinsky, Skokov - arXiv:2012.01810]

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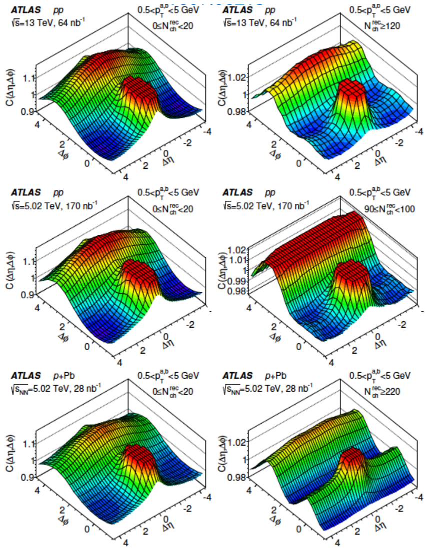
Two particle correlations

Motivation: Ridge structure

[ATLAS Collaboration - arXiv:1609.06213]



- *correlations between particles over large intervals of rapidity peaking at zero and π relative azimuthal angle.*

- observed first at RHIC in Au-Au collisions.

- observed at LHC for high multiplicity pp and pA collisions.

Ridge in HICs $\leftrightarrow$ collective flow due to strong final state interactions

(good description of the data in the framework of relativistic viscous hydrodynamics)

Ridge in small size systems: similar reasoning looks tenuous but hydro describes the data very well.

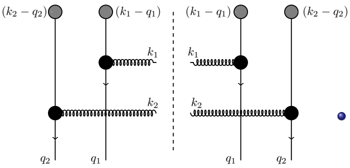
Can it be initial state effect?

idea: *final state particles carry the imprint of the partonic correlations that exist in the initial state.*

Most frequently used mechanism to explain the ridge correlations in the CGC framework:

Glasma graph approach to two gluon production:

[Dumitru, Gelis, McLerran, Venugopalan - arXiv:0804.3858]
[Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan - arXiv:1009.5295]



⋆ Glasma graph calculation contains two physical effects:

- Bose enhancement of the gluons in projectile/target wave function
  [TA, Armesto, Beuf, Kovner, Lublinsky - arXiv:1503.07126]
  $$\sigma|_{BE,P} \propto \Big\{\delta^{(2)}\big[(k_1-q_1)-(k_2-q_2)\big]+\delta^{(2)}\big[(k_1-q_1)+(k_2-q_2)\big]\Big\}$$
  $$\sigma|_{BE,T} \propto \Big\{\delta^{(2)}(q_1-q_2)+\delta^{(2)}(q_1+q_2)\Big\}$$
- Hanbury-Brown-Twiss (HBT) correlations of produced gluons.
  $$\sigma|_{HBT} \propto \Big\{\delta^{(2)}(k_1-k_2)+\delta^{(2)}(k_1+k_2)\Big\}$$
  [Kovchegov,Wertepny - arXiv:1212.1195 / arXiv:1310.6701]
  [TA, Armesto, Beuf, Kovner, Lublinsky - arXiv:1509.03223]

Going beyond the glasma approach in pA collisions

Two particle correlations beyond the glasma graph approach: 2 gluon production in pA collisions

[TA, Armesto, Kovner, Lublinsky - arXiv:1805.07739]

Double Inclusive spectrum:

$$\frac{dN^{(2)}}{d^2k_1d^2k_2} \propto \int_{z_i\bar{z}_i} e^{ik_1\cdot(z_1-\bar{z}_1)+ik_2\cdot(z_2-\bar{z}_2)} \int_{x_iy_i} A^i(x_1-z_1)A^i(\bar{z}_1-y_1)A^j(x_2-z_2)A^j(\bar{z}_2-y_2)$$
$$\times\Big\langle \rho^{a_1}(x_1)\rho^{a_2}(x_2)\rho^{b_1}(y_1)\rho^{b_2}(y_2)\Big\rangle_P$$
$$\times\Big\langle \big[U(z_1)-U(x_1)\big]^{a_1c}\big[U^\dagger(\bar{z}_1)-U^\dagger(y_1)\big]^{cb_1}\big[U(z_2)-U(x_2)\big]^{a_2d}\big[U^\dagger(\bar{z}_2)-U^\dagger(y_2)\big]^{db_2}\Big\rangle_T$$

A^i is the standard WW field.

Projectile averaging: $\langle\rho^{a_1}\rho^{a_2}\rho^{b_1}\rho^{b_2}\rangle = \langle\rho^{a_1}\rho^{b_1}\rangle\langle\rho^{a_2}\rho^{b_2}\rangle + \langle\rho^{a_1}\rho^{a_2}\rangle\langle\rho^{b_1}\rho^{b_2}\rangle + \langle\rho^{a_1}\rho^{b_2}\rangle\langle\rho^{a_2}\rho^{b_1}\rangle$

with $\langle\rho^a(x)\rho^b(y)\rangle = \delta^{ab}\mu^2(x,y)$

Target averaging $\rightarrow$ dipole and quadrupole operators:

$$\langle Q(x,y,z,v)\rangle_T \rightarrow d(x,y)d(z,v)+d(x,v)d(z,y)+\frac{1}{N_c^2-1}d(x,z)d(y,v)$$
$$\langle D(x,y)D(z,v)\rangle_T \rightarrow d(x,y)d(z,v)+\frac{1}{(N_c^2-1)^2}\big[d(x,v)d(y,z)+d(x,z)d(v,y)\big]$$

Integration over the coordinates with translationally invariant dipoles $\Rightarrow$

$$\frac{dN^{(2)}}{d^2k_1d^2k_2} = \frac{dN^{(2)}}{d^2k_1d^2k_2}\bigg|_{dd} + \frac{dN^{(2)}}{d^2k_1d^2k_2}\bigg|_{Q}$$

$\swarrow$ uncorrelated $\qquad$ $\searrow$ correlated

Going beyond the glasma approach in pA collisions - II

Correlated part of the 2-gluon spectrum: $$\frac{dN^{(2)}}{d^2k_1 d^2k_2}\Big|_Q \propto \int_{q_1 q_2} d(q_1)d(q_2)\Big[I_{Q,1}+I_{Q,2}\Big]$$

where

$$\begin{aligned} I_{Q,1} &= \mu^2(k_1-q_1,q_2-k_2)\,\mu^2(k_2-q_2,q_1-k_1)\,L^i(k_1,q_1)L^i(k_1,q_1)\,L^j(k_2,q_2)L^j(k_2,q_2)+(k_2\to -k_2)\\ I_{Q,2} &= \mu^2(k_1-q_1,q_1-k_2)\,\mu^2(k_2-q_2,q_2-k_1)\,L^i(k_1,q_1)L^i(k_1,q_2)\,L^j(k_2,q_1)L^j(k_2,q_2)+(k_2\to -k_2)\end{aligned}$$

with $L^i(k,q)=\Big[\frac{(k-q)^i}{(k-q)^2}-\frac{k^i}{k^2}\Big]$ is the Lipatov vertex.

Generalization to the 3-gluon spectrum:

$$\frac{dN^{(3)}}{d^2k_1 d^2k_2 d^2k_3} = \frac{dN^{(3)}}{d^2k_1 d^2k_2 d^2k_3}\Big|_{ddd} + \frac{dN^{(3)}}{d^2k_1 d^2k_2 d^2k_3}\Big|_{dQ} + \frac{dN^{(3)}}{d^2k_1 d^2k_2 d^2k_3}\Big|_{X}$$

ddd - term: all three gluons are uncorrelated.
dQ - term: one gluon is uncorrelated from the other two.
X-term: all three gluons are correlated.

$$\frac{dN^{(3)}}{d^2k_1 d^2k_2 d^2k_3}\Big|_X \propto \int_{q_1 q_2 q_3} d(q_1)d(q_2)d(q_3)\Big[I_{X,1}+I_{X,2}+I_{X,3}+I_{X,4}+I_{X,5}\Big]$$

Each $I_{X,\alpha}$ contribution: 8 different terms with 3-μ^2 functions and 6 Lipatov vertices.
Total of 40 different terms!

v_2 and correlations

[TA, Armesto, Kovner, Lublinsky, Skokov - arXiv:2012.01810]

Can we compute the correlation of v_2 with total multiplicity?

$$\mathcal{O}_{N,v_2} = \frac{\int d\phi_2 d\phi_3 \; e^{i2(\phi_2-\phi_3)} \int d^2k_1 \frac{dN^{(3)}}{d^2k_1 d^2k_2 d^2k_3}\Big|_X}{\int d\phi_2 d\phi_3 \; e^{i2(\phi_2-\phi_3)} \frac{dN^{(2)}}{d^2k_2 d^2k_3}\Big|_Q \int d^2k_1 \frac{dN^{(1)}}{d^2k_1}}$$

Disclaimer:

- MV model: $\mu^2(k,q) = (2\pi)^2 \mu^2 \delta^{(2)}(k+q)$ & GBW model: $d(q) = \frac{4\pi}{Q_s^2} e^{-q^2/Q_s^2}$
- assume $k_2^2 \sim k_3^2 \gg Q_s^2$ and neglect the terms that exponentially suppressed.
- assume large N_c.

Total multiplicity:

$$\frac{dN^{(1)}}{d^2k_1} \propto \int_{q_1} d(q_1)\, \mu^2(k_1-q_1, q_1-k_1)\, L^i(k_1,q_1) L^i(k_1,q_1)$$

Integration over q_1:

$$\frac{dN^{(1)}}{d^2k_1} = \alpha_s (4\pi)(N_c^2-1)\, \mu^2\, S_\perp e^{-k_1^2/Q_s^2} \left\{ \frac{2}{k_1^2} - \frac{1}{k_1^2} e^{k_1^2/Q_s^2} + \frac{1}{Q_s^2}\left[\mathrm{Ei}\left(\frac{k_1^2}{Q_s^2}\right) - \mathrm{Ei}\left(\frac{k_1^2\lambda}{Q_s^2}\right)\right]\right\}$$

$S_\perp \equiv$ transverse area of the projectile & $\lambda \sim 1/(S_\perp Q_s^2)$ IR cutoff

In pA: $Q_s \sim 1$ GeV and $S_\perp \sim 1/\Lambda^2_{QCD} \rightarrow \lambda \sim 1/(S_\perp Q_s^2) \sim 1/25$ is used in the numerical computations.

v_2 and correlations

2-gluon spectrum and v_2: upon integration over q_2 and q_3, two types of terms arise:

Bose enhancement type:

$$Q_1 = \alpha_s^2 (4\pi)^2 (N_c^2 - 1)\ \mu^4 S_\perp \frac{1}{\pi Q_s^2}\, e^{-(k_2-k_3)^2/2Q_s^2} \Big\{ \Big[\frac{1}{2} + \frac{2^2 Q_s^2}{(k_2+k_3)^2} + \frac{2^4 Q_s^4}{(k_2+k_3)^4} \Big] \frac{1}{k_2^2 k_3^2} \frac{(k_2-k_3)^4}{(k_2+k_3)^4} + Q_s^4 \frac{2^6}{(k_2+k_3)^8} \Big[1 + (k_2^i - k_3^i) \Big(\frac{k_2^i}{k_2^2} - \frac{k_3^i}{k_3^2} \Big) \Big] \Big\} + (k_3 \to -k_3).$$

HBT type:

$$Q_2 = \alpha_s^2 (4\pi)^2 (N_c^2 - 1)\ \mu^4 S_\perp (2\pi)^2 \Big[\delta^{(2)}(k_2+k_3) + \delta^{(2)}(k_2-k_3) \Big] \frac{1}{2} \frac{Q_s^4}{k_2^8}$$

When calculating the $\mathcal{O}_{N,v_2}$ these two terms are ready to be plugged in $\int d\phi_2 d\phi_3\ e^{i2(\phi_2-\phi_3)} \frac{dN^{(2)}}{d^2k_2 d^2k_3}\Big|_Q$

BUT let us first compute

$$v_2^2(k,k',\Delta) = \frac{\int_{k-\Delta/2}^{k+\Delta/2} k_2 dk_2 \int_{k'-\Delta/2}^{k'+\Delta/2} k_3 dk_3 \int d\phi_2 d\phi_3 e^{i2(\phi_2-\phi_3)} \frac{d^2N^{(2)}}{d^2k_2 d^2k_3}}{\int_{k-\Delta/2}^{k+\Delta/2} k_2 dk_2 \int_{k'-\Delta/2}^{k'+\Delta/2} k_3 dk_3 \int d\phi_2 d\phi_3 \frac{d^2N^{(2)}}{d^2k_2 d^2k_3}}$$

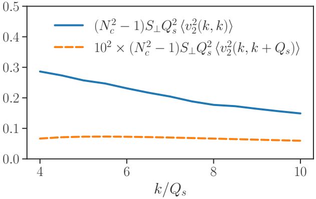
- only the correlated part in the numerator & correlated and uncorrelated parts in the denominator.
- Angular integrations + integrations over the transverse momenta within finite width bins!
- Assume: $k \gg \Delta$, $k' \gg \Delta$, $\Delta \sim Q_s$ and $\lambda = 1/25$.

•v_2^2 is multiplied by the factor $(N_c^2-1)S_\perp Q_s^2$ in order to exhibit universal features of the result applicable to any target. For p-Pb or p-Au: $(N_c^2-1)S_\perp Q_s^2 \sim 200$.

Momentum dependent second flow harmonic: v_2^2

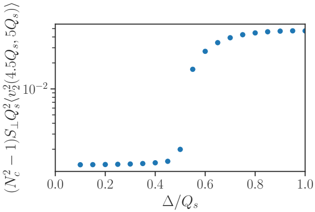
In momentum space: width of the BE correlations $\sim Q_s$ & width of the HBT correlations $\ll Q_s$

non-overlapping bins				overlapping bins
$\Delta < \lvert k - k' \rvert$	$\rightarrow$	$\Delta \approx \lvert k - k' \rvert$	$\rightarrow$	$\Delta > \lvert k - k' \rvert$
only BE contribution		HBT starts to contribute		BE+HBT contribution



- BE dominated regime:
very weak dependence on k.
$\Rightarrow$ BE cont. & (Single inc.)^2 scale with the same power of momentum.

- BE+HBT regime:
HBT $\gg$ BE contribution.
v_2 is rising towards smaller values of k.



sharp transition of v_2 as a function of Δ.

$\Delta/Q_s < 0.5 \rightarrow$ BE dominated regime.
$\Delta/Q_s \sim 0.5 \rightarrow$ HBT starts contributing.

BE+HBT regime: HBT overwhelmingly dominates!

Correlated 3-gluon spectrum

3-gluon spectrum: upon integration over k_1, q_1, q_2 and q_3, again two types of terms arise:
Bose enhancement type of contributions: $(X_1, X_3$ and $X_4)$

$$X_1 = \frac{1}{2}\alpha_s^3(4\pi)^6(N_c^2-1)\,\mu^6\,S_\perp\,e^{-(k_2-k_3)^2/2Q_s^2}\,\frac{1}{k_2^4}$$
$$\times\left\{\left(\frac{1}{2}+Q_s^2\left[\frac{1}{k_2^2}+\frac{2^2}{(k_2+k_3)^2}\right]+Q_s^4\left[\frac{3}{k_2^4}+\frac{2!}{k_2^2}\frac{2^2}{(k_2+k_3)^2}+\frac{2^4}{(k_2+k_3)^4}\right]\right)\frac{1}{k_2^2k_3^2}\frac{(k_2-k_3)^4}{(k_2+k_3)^4}\right.$$
$$\left.+\,Q_s^4\frac{2^6}{(k_2+k_3)^8}\left[1+(k_2^i-k_3^i)\left(\frac{k_2^i}{k_2^2}-\frac{k_3^i}{k_3^2}\right)\right]\right\}.$$

HBT type of contributions: $(X_2$ and $X_5)$

$$X_2 = \alpha_s^3\frac{1}{2}(4\pi)^7(N_c^2-1)\,\mu^6\,S_\perp\left[\delta^{(2)}(k_2+k_3)+\delta^{(2)}(k_2-k_3)\right]\frac{1}{4}\frac{Q_s^6}{k_2^{12}}$$

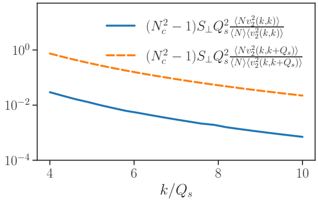
$\mathcal{O}_{N,v_2}$: these terms are ready to be plugged in $\int d\phi_2 d\phi_3\, e^{i2(\phi_2-\phi_3)}\int d^2k_1\,\frac{dN^{(3)}}{d^2k_1d^2k_2d^2k_3}\Big|_X$.

in addition to the angular integrations, we also integrate over bins of width Δ for the two momenta k_2 and k_3:

$$\frac{dN^{(3)}}{d^2k_1d^2k_2d^2k_3}\Big|_X \to \int_{k-\Delta/2}^{k+\Delta/2}k_2dk_2\int_{k'-\Delta/2}^{k'+\Delta/2}k_3dk_3\,\frac{dN^{(3)}}{d^2k_1d^2k_2d^2k_3}\Big|_X$$

v_2 and total multiplicity correlations

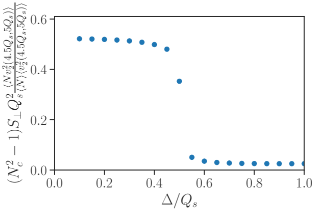
non-overlapping bins				overlapping bins
$\Delta < \lvert k - k' \rvert$	$\rightarrow$	$\Delta \approx \lvert k - k' \rvert$	$\rightarrow$	$\Delta > \lvert k - k' \rvert$
only BE contribution		HBT starts to contribute		BE+HBT contribution



non-overlapping bins: (no HBT contribution to v_2)
overlapping bins: (v_2 is dominated by HBT)

$\mathcal{O}_{N,v_2}|_{HBT}$ is much weaker than $\mathcal{O}_{N,v_2}|_{BE}$.

- $\mathcal{O}_{N,v_2}$ is a decreasing funct. of k.
(N is dominated by soft gluons, correlations we are looking has large k already in the incoming w.f.)



sharp transition of $\mathcal{O}_{N,v_2}$ as a function of Δ.

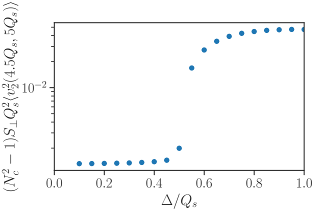
$\Delta/Q_s < 0.5 \rightarrow$ BE dominated regime:
correlation is sizable.

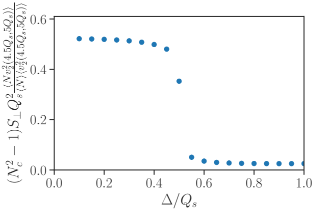
$\Delta/Q_s \sim 0.5 \rightarrow$ HBT starts contributing.

$\Delta/Q_s > 0.5 \rightarrow$ BE+HBT regime:
correlation drops by factor of 30 to 50!

The transition behavior in $\mathcal{O}_{N,v_2}$ is opposite to that of v_2.

Remarks





non-overlapping bins: $\Delta/Q_s < 0.5$ – v_2 is small & sizable correlation between N and v_2 (No HBT contribution)

non-overlapping bins: $\Delta/Q_s > 0.5$ – v_2 is large & negligable correlation between N and v_2 (HBT start contributing)

$$\mathcal{O}_{N,v_2} = \frac{\int d\phi_2 d\phi_3\; e^{i2(\phi_2-\phi_3)} \int d^2k_1 \frac{dN^{(3)}}{d^2k_1 d^2k_2 d^2k_3}\Big|_X}{\int d\phi_2 d\phi_3\; e^{i2(\phi_2-\phi_3)} \frac{dN^{(2)}}{d^2k_2 d^2k_3}\Big|_Q \int d^2k_1 \frac{dN^{(1)}}{d^2k_1}}$$

conclusion:

- $\int d\phi_2 d\phi_3\; e^{i2(\phi_2-\phi_3)} \int d^2k_1 \frac{dN^{(3)}}{d^2k_1 d^2k_2 d^2k_3}\Big|_X$ is a smooth function of Δ.
- the drop in $\mathcal{O}_{N,v_2}$ is driven entirely by the sharp rise $\int d\phi_2 d\phi_3\; e^{i2(\phi_2-\phi_3)} \frac{dN^{(2)}}{d^2k_2 d^2k_3}\Big|_Q$

Summary

• We have computed v_2 & correlations of v_2 with total multiplicity in the dilute-dense CGC framework.

• Our results are valid at large N_c and large transverse momentum.

• Correlations of v_2 and total multiplicity is very small and consistent with the data. (Disclaimer: we do not attempt to describe the data, this is just a qualitative study of the quantum statistics on correlations.)

• We observe a distinct behavior of both v_2 & correlations v_2 and total multiplicity as a function of the transverse momentum bin Δ due to HBT contribution.