Collectivity in small systems: the initial state perspective

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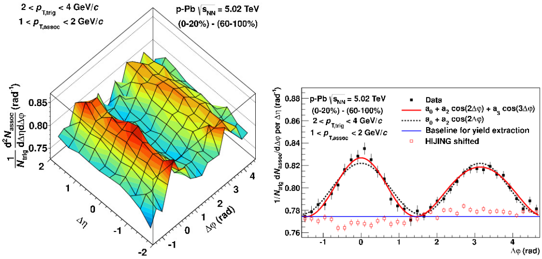
Initial state (a.k.a. CGC) effects in particle correlations.

Famous ridge correlations aka elliptic flow in p-p and p-A.

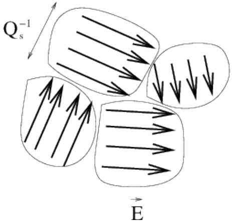


Is it a final state effect (hydro, kinetic theory) or initial state effect (CGC)?
CGC contains several effects that lead to angular correlations: Classical ("color domains", "local density gradients") and Quantum ("Bose enhancement", gluon "HBT"), but could be erased in final state.

Classical correlations

Local anisotropy (a.k.a. color field domains)

Q_s - color correlation length in the target: "color field domains".



Purely classical correlation: gluons that hit the same domain scatter in the same direction (if they have the same charge.)

Density variation

If the density profile is not constant, a dipole scatters differently depending on its orientation. Scattering is more efficient for dipole oriented along the density gradient rather than perpendicular to it.

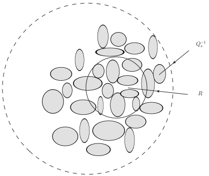
More particles are produced with momentum parallel to density gradient.

Both mechanisms are purely classical: in order to produce correlated particles, the incoming gluons have to sit close to each other in the transverse plain so that they feel the same local structure of the target.

Quantum correlations

Bose enhancement in the incoming wave function a.k.a. "Glasma graphs"

The CGC soft gluon state is "classical" - coherent state. But when averaged over the valence color charges, the density matrix contains Bose Enhancement: the probability to find two gluons at the same transverse momentum (and also opposite momentum) is enhanced.
More gluons come in with $k_\perp = \pm p_\perp \rightarrow$ more gluons are produced with $k_\perp \approx \pm p_\perp$.
Gluonic Hanbury-Brown - Twiss effect



Scattering randomizes color phases in the projectile on transverse scale Q_s^{-1} - the projectile after scattering turns into a bunch of sources of incoherent emission. Typical HBT situation.

What's the difference?

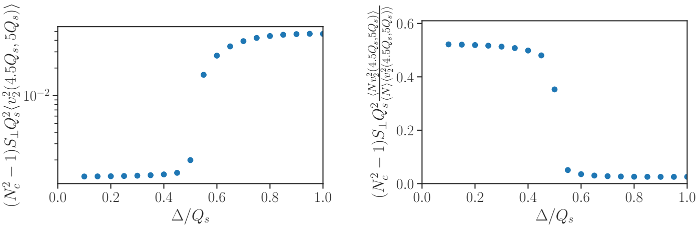
Points close together - classical; points far away - quantum.

Classical are suppressed by $1/Q_s^2 S_{proj}$.

So for hadronic projectile $S_{proj} \sim \Lambda_{QCD}$ and "nuclear" target, $Q_s \sim 1 - 1.5 Gev$ quantum effects are larger.

Interesting features

Some new studies, e.g.: characteristic stricture of v_2 and v_2-multiplicity correlations as a function of bin width: T. Altinoluk, N. Armesto, A.K., M. Lublinsky and V. Skokov, Eur.Phys.J.C 81 (2021) 7, 583



HBT peak is tall but narrow and very weakly correlated with multiplicity. For narrow bins HBT falls out of the window - correlation is dominated by BE. It is not so high, but correlated with multiplicity. For wide bins HBT dominates - v_2 is larger but correlates with multiplicity very weakly.

Old news but still interesting: "quantum" v_2 is **anticorrelted** with initial eccentricity

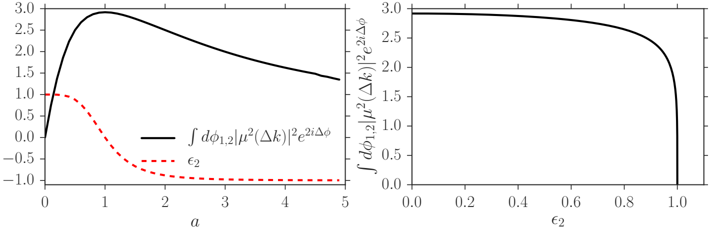
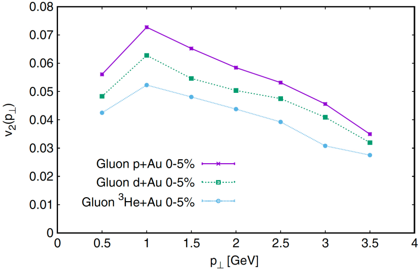


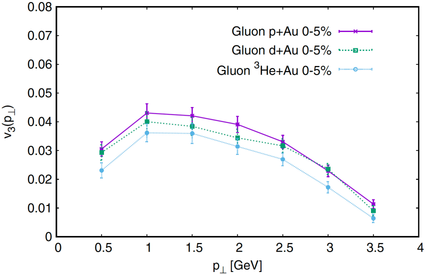
Figure: $v_2^2\{2\}$ versus spatial eccentricity for the HBT contribution. Left panel: eccentricity and $v_2^2\{2\}$ plotted versus parameter a. Right panel $v_2^2\{2\}$ plotted versus the spatial eccentricity. From A.K. and V. Skokov, Phys.Lett.B 785 (2018) 372

Proton an ellipse (with ratio of axis a)- charges distributed within an elliptical area.

Interesting does not mean relevant.

M. Mace, V. Skokov, P. Tribedy and R. Venugopalan, Phys.Rev.Lett. 121 (2018) 5, 052301, Phys.Rev.Lett. 123 (2019) 3, 039901 (erratum); Phys.Lett.B 788 (2019) 161-165, Phys.Lett.B 799 (2019) 135006 (erratum). The hierarchy of v_2 and v_3 for p-A, d-A and He^3-A is reversed compared to experiment, v_4 is too large.





Not relevant, or not very relevant?

Initial state is important at all?

CGC+Glasma+Hydro+ Hadronization study: B.Schenke, C. Shen and P. Tribedy, Phys.Lett.B 803 (2020) 135322

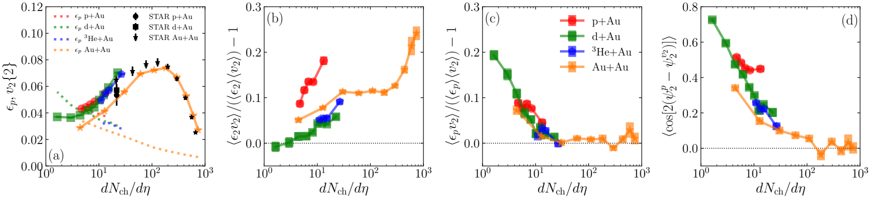


Figure: a) Initial momentum anisotropy and final v_2 as functions of multiplicity compared to STAR datab) Correlation between the initial ellipticity and final v_2. c) Correlation between the magnitude of the initial momentum anisotropy ε_p and final v_2. d) Correlation between the direction of the initial momentum anisotropy (given by ψ_2^p) and the final v_2 (with $\psi_2^{v_2}$ obtained from the flow vector)

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Initial state is clearly important at least for $dN_{ch}/d\eta < 10-15$.

Disentangling effects of initial momentum anisotropy (a.k.a. "CGC initial state") and geometry (a.k.a "hydro") G. Giacalone, B. Schenke, C. Shen, Phys.Rev.Lett. 125 (2020) 19, 192301

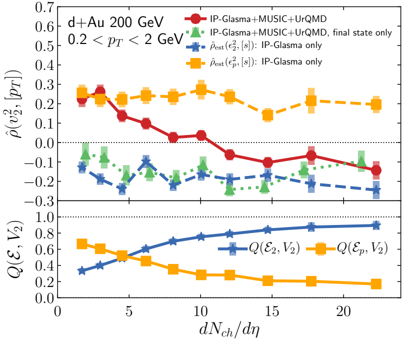

Figure: Upper panel: The correlator $\hat{\rho}(v_2^2, [p_t])$ (circles, solid lines) together with estimators based on the initial geometry ($\hat{\rho}_{\rm est}(\varepsilon_2^2, [s])$, stars) and the initial momentum anisotropy ($\hat{\rho}_{\rm est}(\varepsilon_p^2, [s])$, squares) in d+Au collisions at $\sqrt{s} = 200\,\mathrm{GeV}$. Lower panel: Pearson coefficients between v_2 and the initial ellipticity (stars) and the initial momentum anisotropy (squares), respectively.

Including final state interactions within classical evolution analytically.

V. Skokov and Ming Li; JHEP 06 (2021) 140; JHEP 06 (2021) 141 and in preparation.

Tour de force calculation of finite density corrections to "dilute projectile" limit.

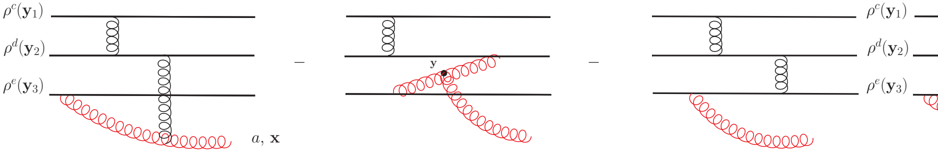

Figure: Sample diagrams contributing to order-g^5 WW field $\alpha_P^{i,a,(5)}(\mathbf{x})$ produced by three color sources.

Explicit analytic expressions for Weizsacker-Williams fields and single inclusive gluon spectrum in terms of the projectile color charges and the target Wilson lines have been obtained.

Corrections are sizable for semihard momenta $\lambda_{QCD} < k_T < Q_s$
Corrections due to final state interactions are significantly more important than those due to nonlinearities of the classical field in the initial state.

Double inclusive spectrum and correlations next?

How about smaller systems? UPC?

Ultraperipheral collisions: ATLAS data on particle correlations - nonvanishng v_2.

First shot at a CGC calculation: Y. Shi, L. Wang, S-Y Wei, B-W Xiao, L. Zheng; Phys.Rev.D 103 (2021) 5, 054017

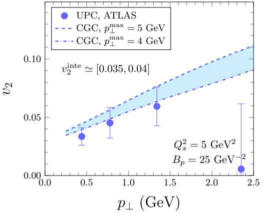

Figure: The ATLAS photo-nuclear data and the resulting v_2 from the CGC model calculation.

Correlations of the right magnitude, but the calculation is very rough and begs a lot of questions.

Gluons emitted in the γ directions, while experimentally most particles are observed in the Pb direction. Only quark-quark correlations in the final state are accounted for - this clearly artificially enhances v_2.

Calculations in more realistic setup are under way (H. Duan, A.K. and V.Skokov) - stay tuned.