

# Quasi Collectivity from Initial State.

Alex Kovner

University of Connecticut

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# The Ridge in p-Pb.

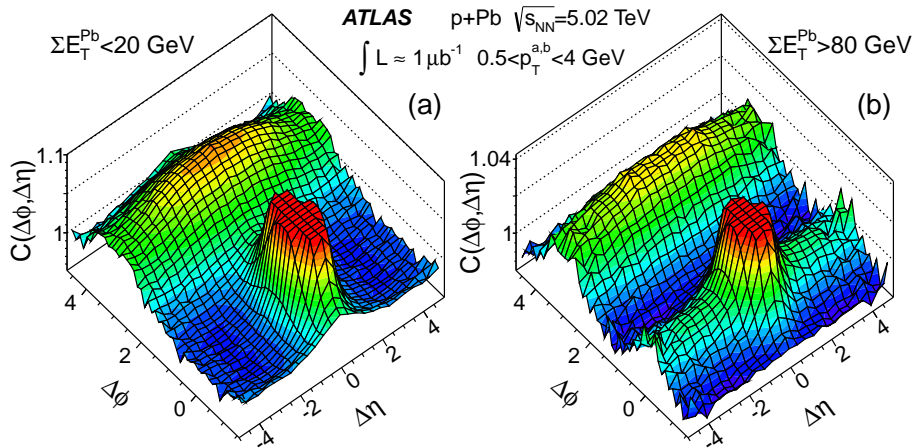
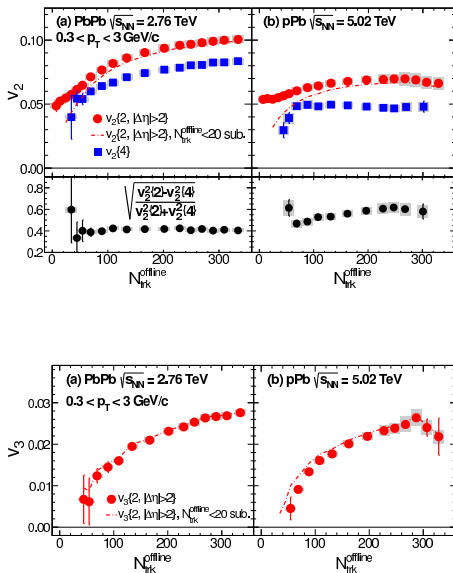


Figure: Ridge in p-Pb at ATLAS,  $\sim 10^{-2}$  events

Correlations point to collective, or at least quasi collective behavior.



"Flow coefficients" measure correlations between the emitted particles, and are believed to encode collectivity of the final state.

$$\frac{d^2 N}{d^2 p_1 d^2 p_2} = 1 + \sum_{n=1}^{\infty} 2V_n(\mathbf{p}_1, \mathbf{p}_2) \cos(n\Delta\phi)$$

$$v_n^2 = \frac{V_n(p_T, p_T^{\text{ref}})}{\sqrt{V_n(p_T^{\text{ref}}, p_T^{\text{ref}})}}; \quad n = 2, 3$$

Analogously for  $v_2^4$  - from four particle inclusive spectrum.

Hydro? Maybe. But: the produced system is small, the momenta involved are quite large  $\sim 8\text{Gev}$ , so hydro is suspect.

Does the ridge and  $v_n$  data necessarily require strong final state interactions?

**Is it possible that nontrivial initial state correlations mimic collectivity (quasi collectivity)?**

# Ridge and Saturation.

**Ridge appears in small fraction, high multiplicity events: "rare" proton configurations with high density. Perhaps saturation (aka CGC) is at play?**

CGC wave function is rapidity invariant: so long range rapidity correlations are its bread and butter.

**Several possible mechanisms to generate correlations from initial state.**

The one explored phenomenologically:

**"Glasma graphs" - aka Bose enhancement.**

Dumitru, Gelis, Jalilian-Marian, Lappi: Phys.Lett. B697 (2011) 21

Altinoluk, Armesto, Beuf, AK and Lublinsky, Phys.Lett. B751 (2015) 448-452

**Successful quantitative effort to describe data:** Dusling and Venugopalan Phys.Rev.Lett. 108 (2012) 262001, Phys.Rev. D87 (2013) 5, 054014.

**In the calculation - no final state interactions. Correlations are "inherited" from the initial state.**

# The CGC hadron wave function.

High energy factorisation: the fast partons are dressed by the soft gluon cloud.

Fast partons: color charge density in the transverse plane  $\rho^a(x_\perp)$ .

Soft gluons: the Weizacker-Williams cloud.

Soft gluon wave function:

$$\Psi[A] = e^{i \int_{x_\perp} b_i[\rho] A_i(x_\perp)} |0\rangle$$

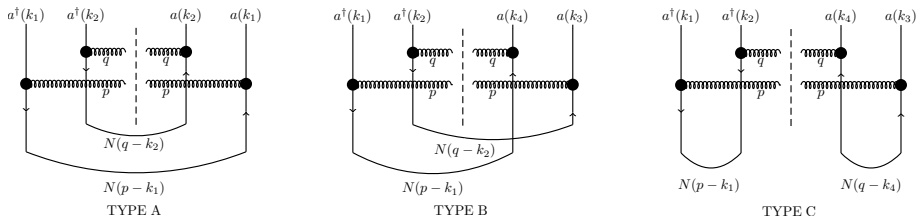
Solution of classical Yang-Mills equation:

$$\partial_i b_i^a(x_\perp) = g \rho^a(x_\perp)$$

$\rho$  has to be averaged over with some weight functional, e.g. simplest Gaussian: McLerran-Venugopalan model (later).

# Bose enhancement.

## Double inclusive gluon production via “Glasma Graphs”:



**Figure:** Glasma graphs for two gluon inclusive production before averaging over the incoming projectile state.

$N(k) = - \int d^2x e^{i\vec{k}\vec{x}} \langle \frac{1}{N_c} \text{tr}[S^\dagger(x)S(0)] \rangle_{\text{Target}}$  - the (adjoint) dipole scattering probability.

# Gluon Production

$$\text{Type A} \propto \int_{k_1, k_2} \langle in | a_a^{\dagger i}(k_1) a_b^{\dagger j}(k_2) a_a^i(k_1) a_b^j(k_2) | in \rangle N(p - k_1) N(q - k_2)$$

$N(k)$  - probability of momentum transfer  $k$  from the target.

**IMPORTANT!**  $k$  - is transverse momentum only.

CGC is boost invariant:  $a_a^i(k) \equiv \frac{1}{\sqrt{Y}} \int_{|\eta| < Y/2} \frac{d\eta}{2\pi} a_a^i(\eta, k)$

$$[a_a^i(k), a_b^{\dagger j}(p)] = (2\pi)^2 \delta_{ab} \delta^{ij} \delta^{(2)}(k - p)$$

The wave function for the soft field is classical:

$$|in\rangle_\rho = \exp \left\{ i \int_k b_a^i(k) \left[ a_a^{\dagger i}(k) + a_a^i(-k) \right] \right\} |0\rangle,$$

Weizsäcker-Williams field  $b_a^i(k) = g \rho_a(k) \frac{ik^i}{k^2}$ .



# The density matrix.

The full hadronic density matrix - has to integrate over  $\rho$  with some weight  $W[\rho]$ .

Take MV model for  $W[\rho]$ .

This defines the density matrix (operator) on the soft gluon Hilbert space:

$$\hat{\rho} = \mathcal{N} \int D[\rho] e^{-\int_k \frac{1}{2\mu^2(k)} \rho_a(k) \rho_a(-k)} e^{i \int_q b_b^i(q) \phi_b^i(-q)} |0\rangle \langle 0| e^{-i \int_p b_c^j(p) \phi_c^j(-p)}$$

with

$$\phi_a^i(k) = a_a^i(k) + a_a^{\dagger i}(-k)$$

Correlators in this  $\hat{\rho}$  Wick factorize in terms of two basic elements:

$$tr[\hat{\rho} a_a^{\dagger i}(k) a_b^j(p)] = (2\pi)^2 \delta_{ab} \delta^{(2)}(k-p) g^2 \mu^2(p) \frac{p^i p^j}{p^4}$$

$$tr[\hat{\rho} a_a^i(k) a_b^j(p)] = tr[\hat{\rho} a_a^{\dagger i}(k) a_b^{\dagger j}(p)] = -(2\pi)^2 \delta_{ab} \delta^{(2)}(k+p) g^2 \mu^2(p) \frac{p^i p^j}{p^4}$$

# The Enhancement.

So that:

$$\begin{aligned} \text{tr}[\hat{\rho} a_a^{\dagger i}(k_1) a_b^{\dagger j}(k_2) a_a^i(k_1) a_b^j(k_2)] &= S^2(N_c^2 - 1)^2 \left\{ \frac{g^4 \mu^2(k_1) \mu^2(k_2)}{k_1^2 k_2^2} \right. \\ &\quad \left. + \frac{1}{S(N_c^2 - 1)} \left[ \delta^{(2)}(k_1 - k_2) + \delta^{(2)}(k_1 + k_2) \right] \frac{g^4 \mu^4(k_1)}{k_1^4} \right\} \end{aligned}$$

The first term is the “classical” square of the density.

The last term is a *bona fide* Bose enhancement contribution.

# Correlated production.

Initial state Bose enhancement  $\rightarrow$  correlation in the final state.

Say projectile has saturation momentum  $Q_s$ , and  $|k_1, k_2| \sim Q_s$ : the momentum transfer in the scattering is  $< Q_s$ , and  $N(p - k_i)$  does not have large effect.

Initial correlations are reflected in the final state (final state interactions aside!).

# This is not HBT!

HBT : Kovchegov and Wertepny; Nucl.Phys. A906 (2013) 50;  
Altinoluk, Armesto, Beuf, AK and Lublinsky, Phys.Lett. B752 (2016) 113

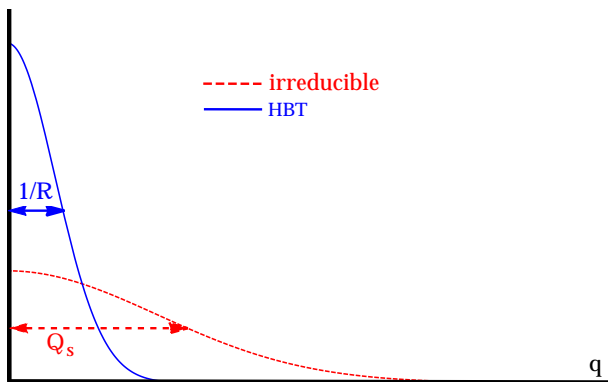


Figure: Schematic separation between the HBT and initial-state Bose signals.

# Bose Correlations not enough.

Good but not good enough.

Bose correlations may dominate two particle inclusive production, but cannot produce  $v_2\{4\}$

Dumitru, McLerran and Skokov, Phys.Lett. B743 (2015) 134

# Density variation.

**Density variation** E. Levin a A. Rezaeian: Phys.Rev. D84 (2011) 034031

Density varies in transverse plane - scattering probability of a dipole depends on its orientation relative to the density gradient.

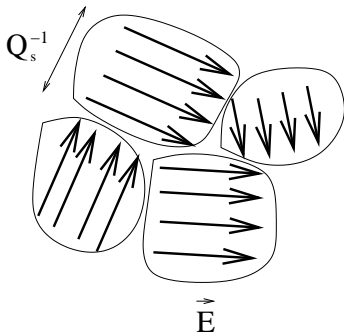
Correlation between produced particles arises due to correlation with the direction of density gradient.

The correlation is large for production at momenta  $p \sim \partial Q_s / Q_s$ .

Has not been explored enough. Correlation is on the scale of density variation. If hot spots - the momentum scale can be pretty large.

# Local Anisotropy: "Color Field Domain" model.

**Local anisotropy - "Domains" of color field** A.K., M. Lublinsky :  
Phys.Rev. D83 (2011) 034017



Like charged particles scatter in the same direction: correlations guaranteed.

Dumirtu and Giannini Nucl.Phys. A933 (2015) 212; Dumitru, McLerran and Skokov, Phys.Lett. B743 (2015) 134 ; Dumitru and Skokov Phys.Rev. D91 (2015), 074006; Lappi, Schenke, Schlichting and Venugopalan, JHEP 1601 (2016) 061

In principle can be  $O(1)$  at large  $N_c$ . However  $O(1)$  effect dies quickly with high energy evolution even if present in initial condition.

AK and M. Lublinsky, Phys.Rev. D84 (2011) 094011

The effect is  $N_c$  suppressed, but even  $O(1/N_c)$  is very important:

Dumitru and Skokov Phys.Rev. D91 (2015), 074006:

$$N_\rho(\vec{r}) = \mathcal{N}(r) \left( 1 + \sum_{n=1}^{\infty} A'_{2n}(r) \cos(2n\phi_r) \right) ; \quad A_{2n} \equiv \frac{\pi}{2} |A'_{2n}|$$

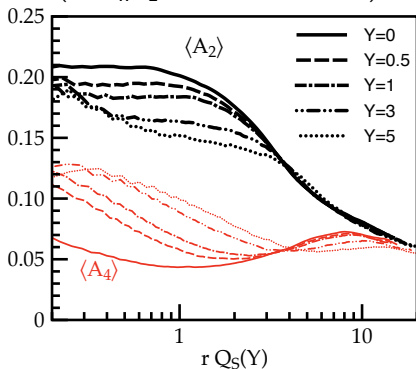


Figure: JIMWLK evolution of  $\langle A_2 \rangle(r)$  and  $\langle A_4 \rangle(r)$ .



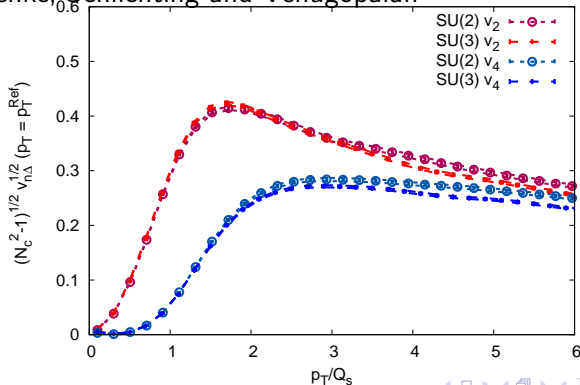
# Why is it important?

$$v_2\{2\}^2 = \frac{1}{N_D} \left( \langle A_2 \rangle^2 + \frac{1}{4(N_c^2 - 1)} \right)$$

$$c_2\{4\} = -\frac{1}{N_D^3} \left( \langle A_2 \rangle^4 - \frac{1}{4(N_c^2 - 1)^3} \right); \quad v_2\{4\} = \sqrt{-c_2\{4\}}$$

If  $A \propto 1/N_c$  - sensible  $v_2\{4\}$ .

Lappi, Schenke, Schlichting and Venugopalan



# Challenges.

Resume: Initial state correlations can produce sizable  $v_2\{2\}$  and describe quantitatively the ridge data.

But there are outstanding challenges.

$$v_2\{4\} = ?$$

Some  $v_2\{4\}$  is produced by the local anisotropy (Color field domain) model.

Probably not enough - only particle scattering on the same domain are correlated, so the correlated signal suppressed by  $1/N_D$  - the number of domains.

## Triangular flow?

$$v_3 = 0 \quad ?$$

The "dilute-dense" CGC formula is symmetric **configuration by configuration**

$$\frac{dN}{d^2p d^2k}(p, k) = \frac{dN}{d^2p d^2k}(p, -k)$$

**Odd harmonics automatically vanish.**

**Not a fundamental problem, but a very stubborn one.**

Production from one Pomeron (dilute-dilute) does not have the symmetry, but produces a wrong sign  $v_3^2$  (back to back).

**Quark production has  $v_3$ , but quark production in  $O(\alpha_s)$  effect, plus quarks are accompanied by antiquarks - so in all a minute effect.**

# Possible ways to resolution.

Recent paper Gotsman, Levin and Maor: HBT effect in CGC produces odd as well as even harmonics. Don't understand - can't comment.

Final state interaction of classical fields - "Glasma".

Schenke, Schlichting and Venugopalan, Phys.Lett. B747 (2015) 76

Classical evolution generates  $v_3 \sim 0.03$ , at  $p_T \sim 1 - 2$  GeV, which drops fast with  $p_T$ .

Some questions about controllability when applied to p-A.

**Maybe we are oversimplifying CGC?**

# KLM back from the dead?

Old idea due to **Kharzeev, Levin and McLerran**: in the dense CGC wave function a large transverse momentum of any gluon is balanced by many smaller momenta of other gluons.

This would produce  $v_3$ : more gluons are correlated forward than backward. Should also contribute to  $v_2\{4\}$  - more than two particles are correlated. Not the case in the classical field limit (coherent state)

$$\Psi[A] = e^{i \int_{x_\perp} b_i[\rho] A_i(x_\perp)} |0\rangle$$

**But the dense CGC state is not really coherent**: AK, Lublinsky and Wiedemann JHEP 0706 (2007) 075; Altinoluk, AK, Lublinsky, Peressutti JHEP 0903 (2009) 109 .

$$\Psi[A] = e^{i \int_{x_\perp} b_i(x_\perp) A_i(x_\perp)} e^{-\int_{x_\perp, y_\perp} A_i(x_\perp) \Lambda_{ij}(x_\perp, y_\perp) A_j(y_\perp)} |0\rangle$$

Explore the Gaussian correction to the CGC state

AK, Lubilnsky and Skokov - work in progress

First results: no symmetry  $(p, k) \rightarrow (p, -k)$  - odd moments do not vanish.  
 $v_3^2$  seems to have the correct sign.

More work needs to be done

Stay tuned.