

Initial state correlations.

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Motivation

Collinear factorization : all that matters is the total number of partons.
Hadrons are much more interesting than the parton model, even at not very low p_{\perp} .

More and more structure of the proton wave function is being explored:
TMD's, GPD's, multiple parton interactions.

Some are still "averages". Life is in the fluctuations/correlations, and we do not know much about them yet.

In particular, can it be that correlations in the initial state have something important to say about correlations between produced particles observed in $p - p$ and $p - A$ collisions?

This talk is about a certain type of correlations, and only within a limited framework: saturation, or CGC.

The Ridge in Double Inclusive Hadron Production in p-p.

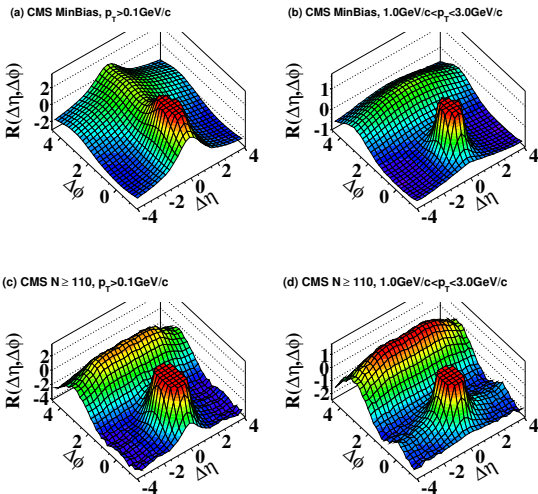


Figure: Ridge in p-p at CMS circa 2010, $\sim 10^{-6}$ events

Ridge in p-Pb.

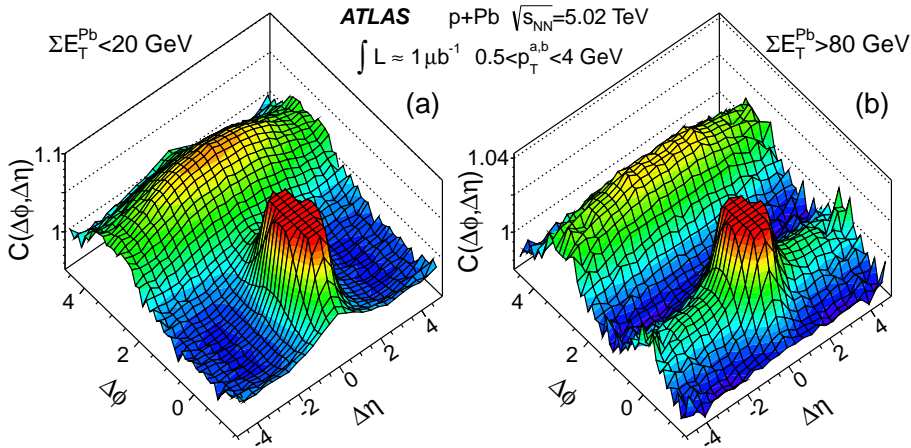
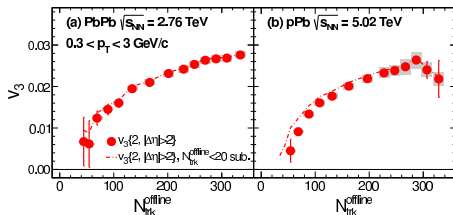
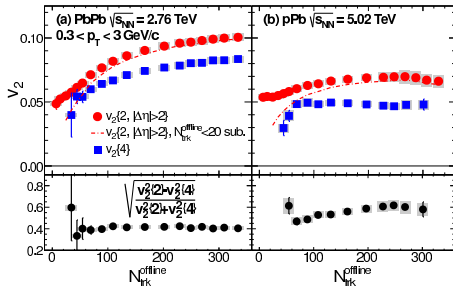


Figure: Ridge in p-Pb at ATLAS, $\sim 10^{-2}$ events

Things got more interesting.

The 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. For double inclusive spectrum

$$\frac{d^2 N}{d^2 p_1 d^2 p_2} \propto 1 + \sum_{n=1}^{\infty} 2V_n(\mathbf{p}_1, \mathbf{p}_2) \cos(n\Delta\phi)$$
$$v_n^2 = \frac{V_n(p_T, p_T^{\text{ref}})}{\sqrt{V_n(p_T^{\text{ref}}, p_T^{\text{ref}})}}; \quad n = 2, 3$$

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

Hydro codes seem to describe the data on v_n .

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

Even more exciting: recent CMS and ATLAS analysis of p-p at LHC - ridge (possibly) persists even in MIN. BIAS events, and below.

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.

Initially ridge was found in small fraction, high multiplicity events: "rare" proton configurations with high density. Perhaps saturation is at play?

Several possible mechanisms to generate correlations from initial state.

The one explored phenomenologically:

"Glasma graphs" Dumitru, Gelis, Jalilian-Marian, Lappi: Phys.Lett. B697 (2011) 21 (arXiv:1009.5295)

Followed by a quantitative effort to describe data: Dusling and Venugopalan Phys.Rev.Lett. 108 (2012) 262001 (arXiv:1201.2658); arXiv:1302.7018

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

Q: What is the physics of "Glasma graphs"?

A: Bose enhancement of gluons in the hadronic wave function.

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:

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

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

Bose Enhancement.

Consider bosonic state with occupation numbers $n^i(p)$:

$$|\{n^i(p)\}\rangle \equiv \prod_{i,p} \frac{1}{\sqrt{n^i(p)!}} (a_i^\dagger(p))^{n^i(p)} |0\rangle, \quad i = 1, \dots, N$$

Mean particle density:

$$n \equiv \langle a^{\dagger i}(x) a^i(x) \rangle = \sum_{i,p} n^i(p)$$

Density-density correlation?

$$D(x, y) \equiv \langle a^{\dagger i}(x) a^{\dagger j}(y) a^i(x) a^j(y) \rangle$$

Calculate in the momentum space:

$$\begin{aligned} \langle a^{\dagger i}(p) a^{\dagger j}(q) a^i(l) a^j(m) \rangle &= \delta(p-l) \delta(q-m) \sum_i n^i(p) \sum_j n^j(q) \\ &\quad + \delta(p-m) \delta(q-l) \sum_i n^i(p) n^i(q) \end{aligned}$$

So that:

$$D(x, y) = n^2 + \sum_i \left| \int \frac{d^3 p}{(2\pi)^3} e^{ip(x-y)} n^i(p) \right|^2; \quad D(p, k) = \left[\sum_i n_i(p) \right] \left[\sum_j n_j(k) + \delta(k-p) \sum_i (n_i(p))^2 \right]$$

Bose Enhancement in CGC?

Bose enhancement is pretty generic, but not present in classical states.

Coherent state:

$$|b(x)\rangle \equiv \exp\left\{i \int d^3x b^i(x)(a^i(x) + a^{\dagger i}(x))\right\} |0\rangle$$

A trivial calculation gives

$$\langle b(x) | a^{\dagger i}(x) a^i(x) | b(x) \rangle = b^i(x) b^i(x)$$

$$\langle b(x) | a^{\dagger i}(x) a^{\dagger j}(y) a^i(x) a^j(y) | b(x) \rangle = b^i(x) b^i(x) b^j(y) b^j(y)$$

so

$$D(x, y) = n(x)n(y)$$

CGC is “classical fields”: can they produce Bose Enhancement?

The answer is Yes.

First things first.

Double inclusive gluon production via “Glasma Graphs”:

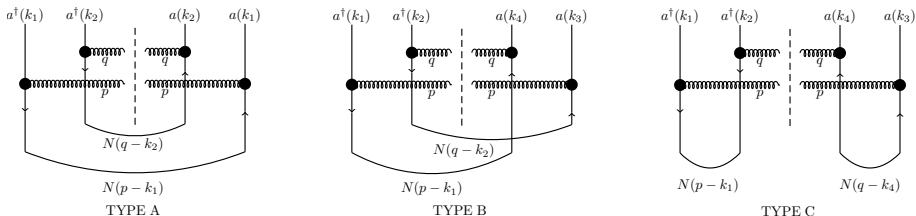


Figure: Glasma graphs for two gluon inclusive production before averaging over the incoming projectile state.

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

But the full hadronic wave function is not: one has to integrate over ρ with some weight $W[\rho]$.

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

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

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

$$\hat{\rho} = e^{-\int_k \frac{g^2 \mu^2(k)}{2k^4} k^i k^j \phi_b^i(k) \phi_b^j(-k)} \left\{ \sum_{n=0}^{+\infty} \frac{1}{n!} \left[\prod_{m=1}^n \int_{p_m} \frac{g^2 \mu^2(p_m)}{p_m^4} p_m^i \phi_{a_m}^i(p_m) \right] |0\rangle \right. \\ \left. \times \langle 0| \left[\prod_{m=1}^n p_m^j \phi_{a_m}^j(-p_m) \right] \right\} e^{-\int_{k'} \frac{g^2 \mu^2(k')}{2k'^4} k'^i k'^j \phi_c^i(k') \phi_c^j(-k')}$$

with

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

The Enhancement.

Easy to show that correlators in this $\hat{\rho}$ Wick factorize in terms of two basic elements:

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

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

So that:

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

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!).

Pauli blocking?

Gluons are Bose enhanced: is there Pauli blocking for quarks?

Yes, but different : for Quark-Quark production we find **short range** Pauli blocking.

There should be depletion of the ridge at $\Delta\eta \sim 2$ if hadrons originate from quarks!

Perhaps open charm-open charm correlations can be measured and analysed?

Conclusions.

It's kinda interesting. Initial state correlations should be observable in some way.

Maybe it is not the ridge. But everything that may happen, will happen at some point.