Transverse radial expansion and 2-particle correlations in ultrarelativistic nuclear collisions

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Outline:
- Transverse expansion and the Blast Wave parameterization
- Correlation functions. 2-particle pt correlation. Superposition of independent collisions and centrality dependence.
- Correlations due to transverse radial flow
  > p_t correlations
  > Elongation of rapidity correlations with centrality; narrowing of the Balance Function.
  > Azimuthal correlations & Balance function in
  > Jet tomography
- Summary

Radial expansion is treated as given. (Not necessarily as due to pressure in thermalized matter, could be considered a la “parton wind”; but numerical calculations are done in the blast wave model).
I will argue that radial expansion “brings” totally new mechanism for 2-particle momentum correlations, not present in NN-collisions.
Transverse radial expansion


Blast wave parameterization (Schnedermann, Sollfrank, Heinz, PRC 48, 2462 (1993), \(d^3n/d^3p \sim e^{-E/T}\)) of the source at freeze-out:

\[
\frac{Ed^3n}{d^3p} \propto \int_0^R rdr \int d\eta d\phi_s m_t \cosh(y-y_s) \exp\left[- \frac{m_t \cosh(y-y_s) \cosh(\rho_t) - p_t \sinh(\rho_t) \cos(\varphi-\varphi_s)}{T}\right]
\]

\[
\frac{d^3n}{dy d^2 p_t} \propto \int_0^R rdr m_t K_1(\beta_t) I_0(\alpha_t); \quad \beta_t \equiv \frac{m_t}{T} \cosh(\rho_t); \quad \alpha_t \equiv \frac{p_t}{T} \sinh(\rho_t)
\]

Parameters: T-temperature, velocity profile \(r \times r\)

Note: uniform source density at \(r < R\) has been assumed.
Transverse radial expansion, II


Results for $n=0.5$ and $n=2$ are shown. Note insensitivity to the actual velocity profile.

$$\rho_t \propto r^n$$

$$\left\langle \rho_t^2 \right\rangle = \left\langle \rho_t \right\rangle^2 \frac{(2+n)^2}{(4n+4)}$$
“Elementary” NN-collision. Correlation functions.

\[
\int dy \, \rho_1(y) = \langle n \rangle
\]

\[
\int dy_1 \int dy_2 \rho_2(y_1, y_2) = \langle n(n-1) \rangle
\]

Distribution of “correlated” pairs:

\[
C(y_1, y_2) = \rho_2(y_1, y_2) - \rho_1(y_1) \rho_1(y_2)
\]

Distribution of “associated” particles (2) per “trigger” particle (1)

\[
B(y_1, y_2) = \frac{C(y_1, y_2)}{\rho_1(y_1)}
\]

“Probability” to find a “correlated” pair

\[
R(y_1, y_2) = \frac{C(y_1, y_2)}{\rho_1(y_1) \rho_1(y_2)}
\]

Correlations are due to local charge(s) conservation, resonances, due to fluctuations in number of produced strings, e.g. number of qq-collisions.

At midrapidity, the probability to find a particle is about 60% larger if one particle has been already detected.

\[
\langle n(n-1) \rangle \approx 1.6 \langle n \rangle^2
\]
2-particle $p_t$ correlations: $\langle \delta p_{t,1} \delta p_{t,2} \rangle; \; \delta p_{t,i} = p_{t,i} - \langle p_t \rangle$

$$R \approx \frac{\sqrt{\langle \delta p_{t,1} \delta p_{t,2} \rangle}}{\langle p_t \rangle}$$

Data: G. Westfall (STAR), QM2004

Fig. 2. Normalized di-verse momentum distribution of average trans-
function of cms energy.
Contributions to $R$ from statistical fluctuations of $p_T$ are re-
moved by the method described in the text.

$\langle \delta p_{t,1} \delta p_{t,2} \rangle / \langle p_t \rangle^2 \approx 0.014$

Production via $N_c$ clusters ($N_c \sim N_{part}/2$) [e.g. independent NN collisions]

$$\langle \delta p_{t,1} \delta p_{t,2} \rangle_{AA} = D_{N_{coll}} \langle \delta p_{t,1} \delta p_{t,2} \rangle_{NN}$$

$$D_{N_{coll}} = \frac{\langle n(n-1) \rangle_{NN}}{(N_{coll} - 1) \langle n \rangle_{NN}^2 + \langle n(n-1) \rangle_{NN}}$$
Radial flow $\Rightarrow$ mean $p_t$ correlations

All particles produced in the same NN-collision (qq-string) experience the transverse radial "push" that is
(a) in the same direction (leads to correlations in phi)
(b) the same in magnitude ($\Rightarrow$ correlations in $p_t$)

Just a few "details":
- Long range rapidity correlations ("bump"-narrow in phi and wide in rapidity, charge independent)
- Stronger 2-particle $p_t$ correlation in narrow phi bins
- Narrowing of the charge balance function
  \( \Delta p_z \approx m_t \sinh(\Delta y) \) -- increase in $m_t \Rightarrow$ decrease in rapidity separation) [same as in S. Pratt et al, in "late hadronization scenario"]
- Charge correlations in phi. Azimuthal Balance function

Everything as function of centrality (radial flow strength)
Initial and freeze-out configurations

**Uncertainty:** particles are at the same position at the moment of production, but the blast wave parameterization is done at freeze-out

Smearing would depend on the
- thermalization time
- diffusion during the system evolution before freeze-out
- non-zero expansion velocity in pp
Mean $p_t$ is almost insensitive to the actual velocity profile.
The correlations are.

In general, mean $p_t$ is sensitive to the first moment of the respective transverse rapidity distribution while the two particle correlation are measuring the second moment.
Brief comparison to data

Possible reasons for discrepancy:
- diffusion, thermalization time
- spatial source profile (not uniform density in transverse plane, e.g. cylinder shell)
Rapidity correlations

Two possibilities:

- correlation of conserved charges (Balance Functions). In this case the correlation existed already at the production moment would be modified by radial flow.

- Charge independent correlations: particles at large rapidities, initially uncorrelated, become correlated, as all of them are pushed by radial flow in the same direction. For those, one needs either 2d correlations (rapidity x azimuth) or rapidity correlation in DeltaPhi slices.

Charge Balance function

\[ \Delta p_z = m_t \sinh(\Delta y) \approx m_t \Delta y \]

As \( <m_t> \) increases due to the transverse radial flow, the balance function gets narrower.

For the BW parameters used above, \( <m_t> \) indeed increases for about 15-20\%, but the centrality dependence is somewhat different from what is observed in the narrowing of the Balance Function.
Two possibilities:

- correlation of conserved charges (Balance Functions). In this case the correlation existed already at the production moment would be modified by radial flow.

- **Charge independent correlations:** particles at large rapidities, initially uncorrelated, become correlated, as all of them are pushed by radial flow in the same direction. For those, one needs either 2d correlations (rapidity X azimuth) or rapidity correlation in DeltaPhi slices. Shown below - hand drawn sketch.
Azimuthal correlations

Figures are shown for particles from the same NN collision. Dilution factor to be applied!

$n=1, \ T=110 \text{ MeV}$

First and second harmonics of the distribution on the left

Again, the large values of transverse flow, $>0.25$, would contradict "non-flow" estimates in elliptic flow measurements.

No momentum conservation effects has been included. Those would be important for the charge independent (first harmonic) correlations.
AA collision. “Single jet tomography”.

In this picture, the transverse momentum of the associated particles would be a measure of the space position the hard scattering occurred.

The plot on the right shows particle azimuthal distribution (integrated over all pt’s) with respect to the boost direction. In order to compare with data it should be also convoluted with jet azimuthal distribution relative to radial direction.
summary

1. Transverse radial flow leads to strong space-momentum correlation. In combination with space correlations between particles created in the same NN collision, it leads to characteristic two (and many) particle rapidity, transverse momentum, and azimuthal correlations.

2. This phenomenon provides a natural (at present, qualitative) explanation of the centrality dependence of mean $p_t$ pseudorapidity/azimuthal angle correlations. It can be further used to study the details of the system equilibration/thermalization and evolution (e.g. thermalization time, velocity profile, etc.)

3. Transverse radial flow “push” of particles created in the same NN collision where hard scattering occurred + jet quenching leads to azimuthal correlations of high $p_t$ “trigger” particle with “soft” particles at rather different rapidity. The mean transverse momentum of the associated particles would be a measure of how deep in the system the hard collision occurred.