Forward-backward correlations between intensive observables

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1. Abstract and motivation

The study of the correlations between observables in two separated rapidity windows (the so called long-range forward-backward correlations) has been proposed [1] as a signature of the string fusion and percolation phenomenon [2], which is one of the collectivity effects in ultrarelativistic heavy ion collisions. Later it was realized [3-5] that the investigations of the forward-backward correlations between intensive observables, such e.g. as mean-event transverse momenta, enable to obtain more clear signal about the initial stage of hadronic interaction, including the process of string fusion, compared to usual forward-backward multiplicity correlations. As an example the correlation between mean-event transverse momenta of charged particles in separated rapidity intervals is considered. We show that this type of correlation is robust against the volume fluctuations and the details of the centrality determination.

The calculations are fulfilled both in the simple model with string fusion by introducing a lattice in transverse plane applying dipole-based Monte Carlo string fusion model. The dependence of the correlation strength on the collision centrality is obtained for different initial energies. It is shown that at LHC energy the dependence reveals the decline of the correlation coefficient for most central collisions and Pb-Pb, reflecting the attenuation of color field fluctuations due to the string fusion at large string density. This non-monotonic behavior with centrality is achieved only in heavy ion collisions at LHC, while in Au-Au collisions at RHIC and p-Pb at LHC the string density is not enough to provide a decline of the correlation coefficient for most central collisions. We compare the results with the ones obtained by us using various MC generators.

We demonstrate that this type of correlation is promising for the observation of the signatures of string fusion at the initial stage of hadronic interaction in relativistic heavy ion collisions at LHC energy.

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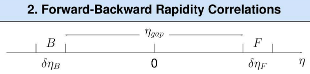
2. Forward-Backward Rapidity Correlations



$\langle B\rangle_F = f(F)$ - the FB correlation function
$\langle B\rangle_F = a + b_{BF}F$ - the linear regression

The correlation coefficient:

$$b_{BF} = \frac{\langle FB\rangle - \langle F\rangle\langle B\rangle}{\langle F^2\rangle - \langle F\rangle^2} = \frac{cov(F,B)}{D_F} \quad (1)$$

For a correlation between relative variables, $F/\langle F\rangle$ and $B/\langle B\rangle$:

$$b^{rel}_{FB} = \frac{\langle F\rangle}{\langle B\rangle} b_{FB} \,. \quad (2)$$

Observables: B, F.
n_B, n_F - the extensive variables ⇒ b_{nn}
p_{tB}, p_{tF} - the intensive variables ⇒ $b_{p_tp_t}$

The Long-Range multiplicity Correlations (LRC): b_{nn} at large η_{gap}.
A. Capella and A. Krzywicki, Phys.Rev.D**18**, 4120 (1978)
The locality of strong interaction in rapidity ⇒ SRC
(SRC - Short-Range Correlations).
The event-by-event variance in the number of cut pomerons (strings) ⇒ LRC.

But event-by-event fluctuations in the number of cut pomerons (strings) (the "volume" fluctuations) do not lead to the correlation between the intensive variables, e.g. the p_{tB}-p_{tF} correlation ($b_{p_tp_t}$).

So the LR p_{tB}-p_{tF} correlation indicates the fluctuations in "quality" of sources.

3. Versions of string fusion

local fusion (overlaps)
M.A. Braun, C. Pajares Eur.Phys.J.**C16**, 349, (2000)

$$\langle n\rangle_k = \mu_0\sqrt{k}\, S_k/\sigma_0 \,, \quad \langle p_t^2\rangle_k = p_0^2\sqrt{k} \,, \quad k = 1,2,3,... \quad (3)$$

global fusion (clusters)
M.A.Braun, F. del Moral, C.Pajares, Phys.Rev.**C65**, 024907, (2002)

$$\langle p_t^2\rangle_{cl} = p_0^2\sqrt{k_{cl}} \,, \quad \langle n\rangle_{cl} = \mu_0\sqrt{k_{cl}}S_{cl}/\sigma_0 \,, \quad k_{cl} = k\sigma_0/S_{cl} \quad (4)$$

The versions of SFM with the finite lattice in transverse plane [5-7]

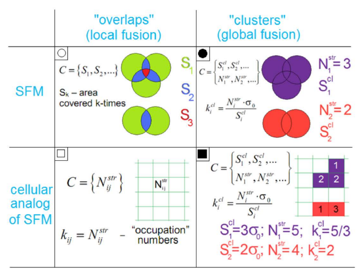


Figure 1: *Various versions of string fusion*

4. Dipole-based MC SFM model [8]

- Partonic dipole-based picture of nucleons interaction.
- Energy and angular momentum conservation in the initial state of a nucleon.
- The probability of dipoles interaction depends on their transverse coordinates with effective coupling:

$$f = \frac{\alpha_S^2}{2}\ln^2\frac{|\vec r_1 - \vec r_1'||\vec r_2 - \vec r_2'|}{|\vec r_1 - \vec r_2'||\vec r_2 - \vec r_1'|}, \quad (5)$$

where $(\vec r_1, \vec r_2), (\vec r_1', \vec r_2')$ are transverse coordinates of the projectile and target dipoles

- With confinement effects taking into account, the probability amplitude is:

$$f = \frac{\alpha_S^2}{2}\left[K_0\left(\frac{|\vec r_1 - \vec r_1'|}{r_{max}}\right) + K_0\left(\frac{|\vec r_2 - \vec r_2'|}{r_{max}}\right) - K_0\left(\frac{|\vec r_1 - \vec r_2'|}{r_{max}}\right) - K_0\left(\frac{|\vec r_2 - \vec r_1'|}{r_{max}}\right)\right]^2 . \quad (6)$$

Here r_{max} is characteristic confinement scale.

- Multiplicity and transverse momentum are calculated in the approach of colour strings, stretched between projectile and target partons, taking into account their finite rapidity width and local cellular string fusion.
- Strings – independent Poisson emitters of charged particles.
- Every parton can interact with other one only once (contrary to Glauber supposition of constant nucleon cross section).
- Parameters of the model are constrained from the p-p, p-Pb and Pb-Pb data on total inelastic cross section and multiplicity.

5. Centrality class width dependence of forward-backward correlations

For large homogeneous string density the following explicit analytical asymptotic of the LR correlation coefficient between mean-event transverse momenta has been obtained [7]:

$$b^{rel}_{nn} = \frac{\omega_\eta\mu_F}{\omega_\eta\mu_F + 4\omega_\mu\sqrt{\eta}} \,, \qquad b^{rel}_{p_tp_t} = \frac{\omega_\eta\mu_F}{\omega_\eta\mu_F + 16\gamma\sqrt{\eta}} \,. \quad (7)$$

Note that ω_μ characterizes the fluctuations in the number of particles produced from a string, ω_η characterizes strings density fluctuation.

The γ characterizes the transverse momentum distribution from one initial string (see table). For a distribution with one dimensional parameter it does not depend on string fusion, then it can be found from data:

$$\gamma = \frac{\langle\langle p_t^2\rangle\rangle - \langle\langle p_t\rangle\rangle^2}{\langle\langle p_t\rangle\rangle^2} \,,$$

note that the $\langle\langle ...\rangle\rangle$ means averaging over tracks from all events.

The feature of the expression (7) for the coefficient of the pt–pt correlation in which it differs from n–n correlation is its independence of ω_μ , i.e., independence of the variance of the number of particles formed during string fragmentation. This makes pt–pt correlations robust against volume fluctuations and the details of the centrality selection.

In figure 2 the calculations in a more realistic MC model with string fusion are shown [9, 10].

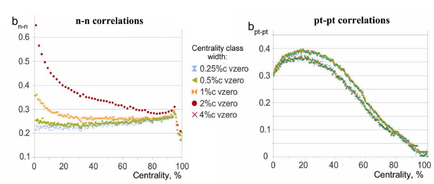


Figure 2: *Centrality dependence of nn (left) and p_t-p_t (right) correlations for different centrality class width at LHC energy in MC model with string fusion*

The results show that n-n correlations strongly depend on the width of the centrality class, changing their centrality behaviour from increase to decrease with centrality, when the centrality class is squeezed.

In contrast, p_t-p_t, the correlation between intensive variables, doesn't depend on the centrality class width being robust against volume fluctuations.

This property also belongs to other forward-backward correlations between intensive observables, for example, correlations involving mean event strangeness (S) – p_t-S and S-S correlations [11, 12].

6. Results in dipole-based MC SFM model

In dipole-based Monte Carlo string fusion model [8,9] we have studied different colliding systems at RHIC and LHC energies.

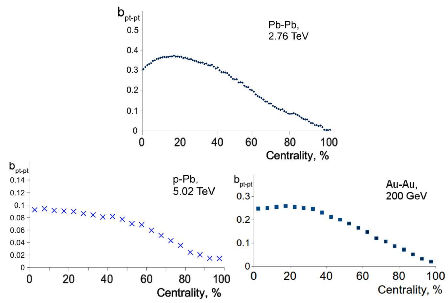


Figure 3: *Centrality dependence of $b_{p_t\text{-}p_t}$ for Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV, for p-Pb at $\sqrt{s_{NN}}$=5.02 TeV and Au-Au at $\sqrt{s_{NN}}$=200 GeV. MC simulations at r_{str}=0.2 fm*

The results show that non-monotonic behaviour of b_{pt-pt} with centrality is achieved in heavy ion collisions at LHC, while in Au-Au collisions at RHIC and p-Pb at LHC the string density is not enough to provide a decline of the correlation coefficient for most central collisions.

7. Mean pt-pt correlations in different models

We compared the predictions of available Monte Carlo generators for p_t-p_t correlations at LHC energy:

- MC model with string fusion (see above).
- THERMINATOR 2 (THERMal heavy IoN generATOR 2) [13]. Based on parametrized freeze-out hypersurface, Cooper-Frye particlization + decays.
- HIJING (Heavy Ion Jet INteraction Generator) [14]. Gluon shadowing + Jet quenching.
- DPMJET, two-component Dual Parton Model, based on the Gribov-Glauber approach [15]. Soft + hard, fragmentation of partons by the Lund model.
- AMPT (A Multi-Phase Transport Model for Relativistic Heavy Ion Collisions). [16]. Shadowing, Zhang's Parton Cascade, string melting, relativistic transport.

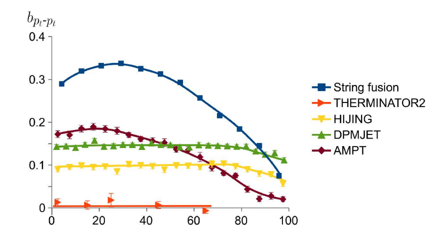


Figure 4: *Centrality dependence of $b_{p_t\text{-}p_t}$ for Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV in different Monte Carlo models*

The results show that the model with parametrized initial sates shows zero correlation coefficient. In the models, which include only initial state shadowing and include soft+hard components, the forward-backward pt-pt correlation is small and independent on centrality.

The relativistic transport model and string fusion model demonstrate significant centrality dependence of $b_{p_tp_t}$ as well as its non-monotonic behaviour.

The comparison clearly shows that p_t-p_t forward-backward correlation and its centrality dependence is sensitive to the initial stages of heavy ion collisions.

8. Summary and conclusions

The dependence of the correlation strength between mean-event transverse momenta on the collision centrality is obtained for different initial energies. It is shown that above RHIC energy the dependence reveals the decline of the correlation coefficient for most central collisions, reflecting the attenuation of color field fluctuations due to the string fusion at large string density.

The long-range correlation between intensive observables, being robust against the volume fluctuations and the details of the centrality determination, enables to obtain the signatures of string fusion at the initial stage of hadronic interaction in relativistic heavy ion collisions at LHC energy.

It would be interesting to study forward-backward pt-pt correlations in fully Event-by-event hydrodynamical models, like iEBE-VISHNU or EKRT to compare the results.

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