Long-range correlations in $pp$ and $A$-$A$ collisions

Grigori Feofilov (St. Petersburg State University)

for the ALICE collaboration

IS2013 International Conference on the Initial Stages in High-Energy Nuclear Collisions
September 8-14 2013, Illa da Toxa (Galicia-Spain)
http://igfae.usc.es/is2013/
Motivation: Long range forward-backward correlations

The initial conditions for the QGP formation in A-A collisions:

**Color string fusion phenomenon (SFM)**
M.A.Braun and C.Pajares

**vs. Color Glass Condensate (CGC) and Glasma flux tubes**, L.McLerran,
Nucl.Phys.A699,73(2002);
T. Lappi and L. McLerran,

Schematics of strings formed just after the collision in cases of lower and of higher energy.

Different predictions for correlation strength behaviour with centrality in Pb-Pb collisions at the LHC.

→ **pp** collisions as a benchmark for Pb-Pb analysis.
Additional motivation: Forward–backward correlations and event shapes as a tool to tune color reconnection and MPI in PYTHIA

Extension into azimuthal dimension

Correlation strength distributions for charged particles for the DW tune for the three different combinations of $\varphi$ regions, defined with respect to the lead particle trajectory.

Charged particles produced in pp, p-A or A-A collisions are detected in two separated pseudorapidity intervals (windows) called Forward (F) and Backward (B).

Some observables are measured event-by-event in these F and B $\eta$ windows:

Types of correlations:
- $n_B - n_F$ - the correlation between charged particle multiplicities in backward (B) and forward (F) rapidity windows (n-n correlation)
Definition of the FB multiplicity correlation coefficient

For symmetrical windows $b_{corr}^{rel} = b_{corr}$

Relative variables are being used in our present study.
Data Analysis

Long-range correlations in pp collisions at LHC energies (0.9, 2.76 and 7 TeV)
pp collisions data at 0.9, 2.76 and 7 TeV: Selection of $\eta$-window pairs in ALICE

$\eta_{\text{gap}}$ – distance between windows ($\eta_{\text{sep}}$ – between the centers)

$\delta \eta$ – windows width

Data collected:
900 GeV (2 Mln events)
2.76 TeV (10 Mln events)
7 TeV (6.5 Mln events)

Correlation coefficient $b_{\text{corr}}$ is calculated for every configuration of $\eta$-windows pair.

$p_T$ range: 0.3-1.5 GeV/c

“soft” physics domain!
Calculation of $b_{corr}$ and correction procedures

- Calculation:
  1) by linear regression
  2) using correlator formula

- Corrections (three alternative procedures):
  1) by correcting $b_{corr}$ raw values
  2) by correcting
  3) by extrapolation of $b_{corr}$ to corrected $<nF>$ values

$\langle n_B n_F \rangle$, $\langle n_B \rangle$, $\langle n_F \rangle$ and $\langle n_F^2 \rangle$

Correction factors are found to be of the order of 5-10%  
Systematic uncertainties are of the order 2-5%

<table>
<thead>
<tr>
<th>Sources</th>
<th>0.9 TeV</th>
<th>2.76 TeV</th>
<th>7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC clusters</td>
<td>0.5-3.0%</td>
<td>0.01-0.13%</td>
<td>0.2-0.7%</td>
</tr>
<tr>
<td>ITS clusters</td>
<td>0.6-1.9%</td>
<td>–</td>
<td>0.15-1.4%</td>
</tr>
<tr>
<td>DCA</td>
<td>3.0-4.0%</td>
<td>0.98-1.8%</td>
<td>0.1-0.98%</td>
</tr>
<tr>
<td>VertexZ</td>
<td>0.2-1.1%</td>
<td>0.016-1%</td>
<td>0.015-0.7%</td>
</tr>
<tr>
<td>Method</td>
<td>2.5-4%</td>
<td>2.2-4.2%</td>
<td>1.6-2.8%</td>
</tr>
<tr>
<td>Pile Up</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Total</td>
<td>3.4-4.5%</td>
<td>2.8-4.2%</td>
<td>2.0-3.0%</td>
</tr>
</tbody>
</table>

List of the sources of systematic uncertainty
1) FB multiplicity correlations in separated $\eta$ windows

- correlation coefficient $b_{corr}$ drops with $\eta$ gap
- the slope is constant with the collision energy
- wider windows give higher $b_{corr}$ values
- values of $b_{corr}$ increase with the collision energy
2) Comparison with event generators: FB multiplicity correlations in separated $\eta$ windows

Comparison with generators:
- trends are reproduced
- PYTHIA reproduces the numbers better than PHOJET
- generators give similar estimations at 900 GeV but different at higher energies.
3) FB multiplicity correlations in separated $\eta$ windows as function of windows width (+comparison to the generators). Example for $\eta$ gap = 0

- Correlations grow with windows $\eta$-width for all energies
- Generators give similar estimations at 900 GeV but different at higher energies

Different tunes give both different multiplicity distributions and $b_{\text{corr}}$ values: on the origin of FB correlations and relation to multiplicity fluctuations see A. Capella et.al in Phys. Rep. 236, 225(1994)
Extension into *azimuthal* dimension: study \( n-n \) correlations in \( \eta \) and \( \phi \) separated window pairs

\( \eta \) and \( \phi \) windows pairs chosen for the analysis:
FB multiplicity correlations in separated $\eta$ and $\phi$ windows (...so far in PYTHIA...the experimental data are in progress)

$pp$, 900 GeV
$0.3 < p_T < 1.5$ GeV/c

PYTHIA6, Perugia-2011
3D representation

$pp$, 7 TeV
$0.3 < p_T < 1.5$ GeV/c

→ short-range and long-range contributions are distinguishable
→ non-zero plateau is observed and increases with the energy
FB multiplicity correlations: \( pp, 7 \text{ TeV}, \) look at Pythia8.

Windows are separated in both \( \eta \) and \( \phi \):

Same in “3D”:
- All On
- Decays Off
- MPI Off

\( \text{(non-zero)} \)

\( \text{zero!} \)
PbPb@LHC: example of SFM MC predictions\cite{1} for $b_{\text{corr}}$ for different centrality selection conditions.

![Graph showing correlation strength in SFM for different centrality classes]

- Strong dependence of $b_{\text{corr}}$ ($b_{\text{nn}}$) on centrality determination (!):
  - The correlation strength in SFM decreases for very central events in case if rather narrow centrality classes are selected ($\leq 0.5\%$ in Npart selection).
  - The “volume fluctuations” are obviously playing the role in case of wider centrality classes.

\[ \text{Bins of different centrality class width are shown here in \%} \]

\[ \text{\rightarrow The correlation strength in SFM decreases for very central events in case if rather narrow centrality classes are selected (\leq 0.5\% in Npart selection)} \]

\[ \text{\rightarrow The “volume fluctuations” are obviously playing the role in case of wider centrality classes} \]

\[ \text{[1] V. Kovalenko, V. Vechernin, report HD 043 at INPC 2013, arXiv:1308.6618 [nucl-th], to be published} \]
Strong dependence of $b_{\text{corr}}$ on centrality determination (!): Npart vs. multiplicity (M)

$\rightarrow$ The classes defined by multiplicity selection differ from those selected via Npart.

$\rightarrow$ Decrease of correlation coefficient with centrality can be also demonstrated in sufficiently narrow centrality bins

$\rightarrow$ This will be taken into account in the ongoing analysis of Pb-Pb data

Summary -1: Experimental results

- Forward-backward multiplicity correlations were measured in separated $\eta$ windows for minimum bias $pp$ events in $pp@LHC$ at 0.9, 2.76 and 7 TeV for charged particles with transverse momenta 0.3-1.5 GeV/c.

- A considerable general increase of $b_{corr}$ with the growth of the collision energy is observed.

- $b_{corr}$ increases with the width of $\eta$ windows but

- $b_{corr}$ only slightly decreases with the growth of the gap between the $\eta$ windows

Experimental results for separated $\eta$-\(\phi\) windows are coming.
Summary -2: Model analysis

- Model analysis of $b_{corr}$ in pp collisions@LHC for various configurations of azimuthal sectors enables to separate the short-range (SR) and the long-range (LR) effects:
  - the LR part arises due to event-by-event fluctuation of the number of emitters,
  - the SR part is due to pair correlation between particles produced by the same emitter.
- PYTHIA and PHOJET indicate that the behavior of $b_{corr}$ with azimuth and rapidity is compatible in pp collisions with the multiparticle production by independent string emitters.

SFM vs CGC model: correlation strength behaviour with centrality in Pb-Pb collisions at the LHC

→ will be investigated
Thank you!
Back-up slides
A Large Ion Collider Experiment

- **EMCAL**: $\gamma, \pi^0, \text{jets}$
- **TRD**: Electron ID (TR)
- **PMD**: $\gamma$ multiplicity
- **TPC**: Tracking, PID (dE/dx)
- **PHOS**: $\gamma, \pi^0, \text{jets}$
- **ToF/VZERO**: Trigger
- **L3 Magnet**: $B=0.5T$
- **ACORDE**: Cosmic trigger
- **HMPID**: PID (RICH) @ high $p_T$
- **ToF**: Dipoles Magnet
- **PID**: Dipoles Magnet
- **ITS**: Low $p_T$ tracking PID + Vertexing
- **FMD**: Charged multiplicity
- **MUON**: arm $\mu$-pairs

Not shown: ZDC (at $\pm 116m$)

K. Aamodt et al. (ALICE), JINST, 3, S08002 (2008)
Forward-Backward (Long-Range) correlations

Causality requires appearance of long-range correlations – if they exist – at the very early stages between particles detected in separated rapidity intervals in any type of collisions (pp, pA, AA):

Theoretical Motivation: 
Color string formation and decay

2-stage scenario of color string formation and decay:
A.Capella, U.P.Sukhatme, C.--I.Tan
and J.Tran Thanh Van,
A.B.Kaidalov K.A.Ter-Martirosyan ,

Do these color strings interact
and what is the signal?
Abramovskii V. A., Gedalin E. V., Gurvich E. G., Kancheli O. V. ,

Color string fusion phenomenon:
M.A.Braun and C.Pajares,
FB multiplicity correlations in *pp collisions*:

look at Pythia8

*samples:*

Pythia8 (8170)
Tune 4Cx
Beams:eCM = 7000 ! CM energy of collision

Can switch **on/off** the key event generation steps:

#PartonLevel:MPI = off ! no multiparton interactions
#PartonLevel:ISR = off ! no initial-state radiation
#PartonLevel:FSR = off ! no final-state radiation
#HadronLevel:Hadronize = off ! no hadronization
#HadronLevel:Decay = off ! no decays

100k events were generated for each option set “off”
FB multiplicity correlations, \( pp, 7 \) TeV: look at Pythia8

Take separated in \( \eta \) windows (\( \varphi \) size is \( 2\pi \)):

- MPI Off - removes fluctuations in number of emitting sources

That causes the absence of correlations for distant \( \eta \) windows (\( b_{\text{corr}}=0 \)),

while switching off the other processes leads to reduction of mean multiplicity and of the correlation strength

\(<n_F>=2.23\)
\(<n_F>=1.14\)
\(<n_F>=1.43\)
\(<n_F>=1.41\)
\(<n_F>=0.21\)
\(<n_F>=1.00\)
Model with strings as independent emitters [1,2]

\[ \delta a = \delta \eta \delta \phi / 2\pi \quad - \text{acceptance of the forward and backward windows.} \]

For windows with small acceptances in rapidity and azimuth situated in a mid rapidity region:

\[ b_{\text{corr}} = b^{LR} + b^{SR} \]

\[ b^{LR} = \frac{\omega_N \mu_0 \delta a}{1 + [\omega_N + \Lambda(0, 0)] \mu_0 \delta a} \]

\[ b^{SR} = \frac{\mu_0 \delta a}{1 + [\omega_N + \Lambda(0, 0)] \mu_0 \delta a} \Lambda(\eta_{\text{sep}}, \phi_{\text{sep}}) \]

At \( \Lambda(\eta, \phi) = 0 \) we have

\[ b^{SR}_{\Lambda=0} = 0, \quad \text{but} \quad b^{LR}_{\Lambda=0} = \frac{\omega_N \mu_0 \delta a}{1 + \omega_N \mu_0 \delta a} \neq 0 \]

\( \omega_N \) is the event-by-event \textit{scaled variance of the number of strings}.

\( \mu_0 \) is the average rapidity density of the charged particles produced by one string.

\( \Lambda(\eta, \phi) \) is the pair correlation function of a single string.

Connection of the FB correlation coefficient with two-particle correlation function - 1

By definition the two-particle correlation function $C_2$ is defined through the inclusive $\rho_1$ and double inclusive $\rho_2$ distributions:

$$C_2(\eta_F, \phi_F; \eta_B, \phi_B) = \frac{\rho_2(\eta_F, \phi_F; \eta_B, \phi_B)}{\rho_1(\eta_F, \phi_F) \rho_1(\eta_B, \phi_B)} - 1$$  \hspace{0.5cm} (1)

$$\rho_1(\eta, \phi) = \frac{d^2N}{d\eta d\phi} , \hspace{1cm} \rho_2(\eta_F, \phi_F; \eta_B, \phi_B) = \frac{d^4N}{d\eta_F d\phi_F d\eta_B d\phi_B}$$  \hspace{0.5cm} (2)

To measure the $\rho_1$ one has by definition to take a small window $\delta\eta \delta\phi$ around $\eta, \phi$, then

$$\rho_1(\eta, \phi) \equiv \frac{\langle n \rangle}{\delta\eta \delta\phi} ,$$  \hspace{0.5cm} (3)

here $\langle n \rangle$ is the mean multiplicity in the acceptance $\delta\eta \delta\phi$.
One has to reduce the acceptance until the ratio (3) becomes constant.
To measure the $\rho_2$ one has by definition to take TWO small windows: $\delta \eta_F \delta \phi_F$ around $\eta_F, \phi_F$ and $\delta \eta_B \delta \phi_B$ around $\eta_B, \phi_B$, then

$$\rho_2(\eta_F, \phi_F; \eta_B, \phi_B) \equiv \frac{\langle n_F n_B \rangle}{\delta \eta_F \delta \phi_F \delta \eta_B \delta \phi_B}.$$  \hspace{1cm} (4)

One has to reduce the acceptances of the observation windows until the ratio (4) becomes constant.

So by (3) and (4) the definition (1) means the following experimental procedure of the determination of the correlation function $C_2$:

$$C_2(\eta_F, \phi_F; \eta_B, \phi_B) \equiv \frac{\langle n_F n_B \rangle - \langle n_F \rangle \langle n_B \rangle}{\langle n_F \rangle \langle n_B \rangle},$$  \hspace{1cm} (5)

where $n_F$ and $n_B$ are the event multiplicities in TWO small windows: $\delta \eta_F \delta \phi_F$ around $\eta_F, \phi_F$ and $\delta \eta_B \delta \phi_B$ around $\eta_B, \phi_B$. 
Connection of the FB correlation coefficient with two-particle correlation function - 3

Traditionally one uses the following definition of the FB correlation coefficient:

\[ b_{abs} \equiv \frac{\langle n_F n_B \rangle - \langle n_F \rangle \langle n_B \rangle}{\langle n_F^2 \rangle - \langle n_F \rangle^2} \quad \text{or} \quad b_{rel} \equiv \frac{\langle n_F \rangle}{\langle n_B \rangle} b_{abs} \]  \hspace{1cm} (6)

For small FB windows by (5) we have

\[ b_{abs} = \frac{\langle n_F \rangle \langle n_B \rangle}{D_{n_F}} C_2(\eta_F, \phi_F; \eta_B, \phi_B), \quad b_{rel} = \frac{\langle n_F \rangle^2}{D_{n_F}} C_2(\eta_F, \phi_F; \eta_B, \phi_B) \]  \hspace{1cm} (7)

Note that for small forward window: \( D_{n_F} \to \langle n_F \rangle \).
So by (7) we see that the traditional definition of the FB correlation coefficient in the case of TWO small observation windows coincides with the standard definition of two-particle correlation function \( C_2 \) upto some common factor \( \langle n_B \rangle \) or \( \langle n_F \rangle \), which depends on the width of windows.
Note that one can go in $C_2$ to the variables:

$$\Delta \eta = \eta_F - \eta_B , \quad \eta_C = (\eta_F + \eta_B)/2$$  \hspace{1cm} (8)

$$\Delta \phi = \phi_F - \phi_B , \quad \phi_C = (\phi_F + \phi_B)/2$$  \hspace{1cm} (9)

and EXPERIMENTALLY check up the dependence of the two-particle correlation function $C_2$ on $\eta_C$ for the different configurations and separations between FB observation windows.

Summing up, we see that by the standard definition (1) the experimental determination of the two-particle correlation function $C_2(\eta_F, \phi_F; \eta_B, \phi_B)$ requires (5) the measurements of the event multiplicities $n_F$ and $n_B$ in TWO SMALL windows: $\delta \eta_F \delta \phi_F$ around $\eta_F$, $\phi_F$, and $\delta \eta_B \delta \phi_B$ around $\eta_B$, $\phi_B$, which is performed in our approach.
Connection of the FB correlation coefficient with two-particle correlation function - 5

Note that the so-called di-hadron correlation function

\[ C(\Delta \eta, \Delta \phi) \equiv S/B - 1, \] (10)

which takes into account all possible pair combinations of particles produced in given event in some **ONE LARGE** pseudorapidity window, where

\[ S = \frac{d^2 N}{d \Delta \eta d \Delta \phi} \] (11)

and the \( B \) is the same but in the case of uncorrelated particle production, has only indirect connection with the standard definition (1) of the two-particle correlation function \( C_2(\eta_F, \phi_F; \eta_B, \phi_B) \) and can coincide with it only in the case when the pseudorapidity translation invariance (the independence \( C_2 \) on \( \eta_C \)) takes place. This indirect method can also lead to the loss in \( C(\Delta \eta, \Delta \phi) \) the common "pedestal", which takes place in \( C_2(\Delta \eta, \Delta \phi) \) (see arXiv:1305.0857 for details).
This common “pedestal” in $C_2(\Delta \eta, \Delta \phi)$ is physically important as, for example, in the model with fluctuating number $N$ of the independent identical emitters (strings) one has the following expression for the $C_2(\Delta \eta, \Delta \phi)$:

$$C_2(\Delta \eta, \Delta \phi) = \frac{\omega_N + \Lambda(\Delta \eta, \Delta \phi)}{\langle N \rangle},$$

(12)

where the $\Lambda(\Delta \eta, \Delta \phi)$ is the pair correlation function of a single string and the $\omega_N = D_N/\langle N \rangle$ is the scaled variance of the event-by-event fluctuation of the number $N$ of strings.

Hence by (12) we see that from the height of the “pedestal” ($\omega_N/\langle N \rangle$) one can obtain the important physical information on the magnitude of the fluctuation of $N$ at different energies and centrality fixation.