NA61/SHINE results on fluctuations and correlations in \( p+p \) and \( \text{Be+Be} \) interactions at CERN SPS energies

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Fluctuations and correlations are universal tool to:

- study the onset of deconfinement
- search for the critical point of strongly interacting matter
- study resonance abundances, influence of conservation laws and other properties of strongly interacting matter

http://www.nova-pen.pl
The most interesting region of the phase diagram is accessible at the SPS:

- the onset of deconfinement at $\sqrt{s_{NN}} = 7.6$ GeV
- indications of the critical point located at $\sqrt{s_{NN}} = 17.3$ GeV
The NA61/SHINE experiment performs comprehensive scan with light and intermediate mass nuclei in energy range 13A-158A GeV

Data taking schedule for the strong interactions program and its proposed extension (in gray)

Estimated (NA49) and expected (NA61) chemical freeze-out points PRC 73, 044905
Fluctuations quantities

Two families of quantities which in wounded nucleon model or GCE are:

### Intensive

A ratio of two extensive quantities ($\sim N_W$) is an intensive measure e.g.:

$$\omega[A] = \frac{\langle A^2 \rangle - \langle A \rangle^2}{\langle A \rangle},$$

where $A$ stands for an event quantity.

In WNM $\omega_i = \frac{\text{Var}(a)}{\langle a \rangle} + \langle a \rangle \frac{\text{Var}(N_W)}{\langle N_W \rangle}$, where $a$ - particles produced from single wounded nucleon.

- independent of $N_W$
- depends on fluctuations of $N_W$
- $\omega = 1$ for Poisson distribution

### Strongly intensive

Special combination of extensive quantities can be a strongly intensive measure e.g.:

$$\Delta[A, B] = \frac{1}{C_\Delta} [\langle B \rangle \omega_A - \langle A \rangle \omega_B]$$

$$\Sigma[A, B] = \frac{1}{C_\Sigma} [\langle B \rangle \omega_A + \langle A \rangle \omega_B - 2(\langle AB \rangle - \langle A \rangle \langle B \rangle)]$$

For comparison with the NA49 experiment the $\Phi$ quantity is used:

$$P_T = \sum_{i=1}^{N} p_T, \quad \Phi_{P_T} = \sqrt{P_T \omega[P_T][\sqrt{\Sigma[P_T, N]} - 1]} \quad \Phi_{ij} = \frac{\sqrt{\langle N_i \rangle \langle N_j \rangle}}{\langle N_i + N_j \rangle} \cdot [\sqrt{\Sigma[i, j]} - 1]$$

- independent of $N_W$ and fluctuations of $N_W$
- normalization chosen such that $\Delta[A, B] = \Sigma[A, B] = 1$ for independent particle model and both quantities are dimensionless
- $\Delta[A, B] = \Sigma[A, B] = 0$ in the absence of fluctuations
Energy dependence of $\Sigma[P_T, N]$ and $\Phi_{p_T}$
Energy dependence of $\Delta[P_T, N]$

- Be+Be results close to p+p
- no structures which could be connected to the CP/OD in p+p and Be+Be
- no centrality dependence in Be+Be
- Bose-Einstein statistics and $P_T/N - N$ correlations probably introduce difference between $\Delta$ and $\Sigma$ (PRC 89, 034903)
Comparison with Pb+Pb interactions

In order to compare the $\Phi_{pT}$ results, NA49 cuts have been applied to NA61/SHINE data.

New results of the NA61/SHINE experiment are in agreement with dependence observed by the NA49 experiment.
Charge fluctuations of non-identified particles

Charge fluctuations in Be+Be interactions at 150A GeV/c are studied using $\Delta[N_+, N_-]$ and $\Sigma[N_+, N_-]$ in several pseudorapidity intervals $\delta \eta = 0.2 + i \cdot 0.4$ where $i \in 0...8$.

- both quantities are independent of centrality
- they are $< 1$ possibly due to energy-momentum and charge conservation
- $\Sigma$ decreases significantly with $\delta \eta$ increase. Tendency perfectly reproduced by EPOS.
Fluctuations of identified hadrons produced in strong and EM processes in $p+p$ interactions at 31, 40, 80, 158 GeV/$c$ were studied using the moments of identified particle multiplicity distributions.

- $\omega_{pos+neg} \geq \omega_{pos}$
- $\omega_{p+\bar{p}} \approx \omega_{p}$ as $\langle N_{\bar{p}} \rangle \approx 0$
- $\omega_{p+\bar{p}} < 1$ - baryon number conservation
- $\omega_{K} > 1$ - strangeness conservation (supported by $\omega_{K} > \omega_{K^+} \approx 1$)
- $\omega_{\pi} \uparrow$ with $\sqrt{s_{NN}}$ - KNO-G scaling
- $\omega_{\pi^+} < 1$ - possibly charge conservation
- String models describe data well

They support the KNO-G scaling and conservation laws as a dominant source of the multiplicity fluctuations.
Comparison with 3.5% of most central Pb+Pb collisions

- chemical fluctuations in p+p and Pb+Pb collisions are similar
- \( \Phi_{\pi(p+\bar{p})} \) in p+p > \( \Phi_{\pi(p+\bar{p})} \) in Pb+Pb
- \( \Phi_{\pi K} \geq 0 \) and is similar in both reactions
- \( \Phi_{(p+\bar{p})K} \) close to 0 in both reactions. It changes sign at \( \sqrt{s_{NN}} \approx 8.7 \text{ GeV} \) but \( \Phi_{(p+\bar{p})K} \) in p+p and \( \Phi_{(p+\bar{p})K} \) in Pb+Pb
- for \( \Phi_{\pi(p+\bar{p})} \) and \( \Phi_{\pi K} \) UrQMD agrees with the data
- \( \Phi_{(p+\bar{p})K} \) is energy-independent in UrQMD instead of the observed decrease in Pb+Pb
In order to pinpoint the sources of correlations we can use **two particle correlations in** $\Delta \eta \Delta \phi$.

They allow to disentangle different sources of correlations like:

- jets
- flow
- resonance decays
- quantum statistics
- conservation laws

Correlations are obtained by finding the difference in pseudo-rapidity $\Delta \eta = |\eta_1 - \eta_2|$ and azimuthal angle $\Delta \phi = |\phi_1 - \phi_2|$ between two particles in the same event. Next they are normalized using mixed events.

$$C(\Delta \eta, \Delta \phi) = \frac{N_{\text{pairs}}^\text{mixed}}{N_{\text{pairs}}^\text{data}} \frac{S(\Delta \eta, \Delta \phi)}{M(\Delta \eta, \Delta \phi)},$$

$$S(\Delta \eta, \Delta \phi) = \frac{d^2 N_{\text{signal}}}{d\Delta \eta d\Delta \phi},$$

$$M(\Delta \eta, \Delta \phi) = \frac{d^2 N_{\text{mixed}}}{d\Delta \eta d\Delta \phi}.$$
Structures visible at 158 GeV/c in p+p interactions

- Maximum at \((0, \pi)\) - probably due to resonance decays and momentum conservation
  - strong in unlike-sign pairs
  - visible in positively charged pairs (\(\Delta^{++}\) decay)
  - non-visible in negatively charged pairs

- Enhancement at \((0, 0)\) - probably due to Coulomb or quantum statistics (not strong in unlike-sign pairs, visible in same charge pairs)
Energy dependence from 6.3 GeV up to 7 TeV

Resonance decay hill is more visible at lower energies whereas jets dominate at higher energies.
Energy dependence of $C(0, 0)$ and $C(0, \pi)$

$C(0, 0)$ rises whereas $C(0, \pi)$ decreases with energy dependence.
Summary

- Results on fluctuations and correlations in p+p and Be+Be at 20-158 A GeV beam momentum were shown.
- Fluctuations in p+p and Be+Be interactions are similar and dominated by conservation laws and resonance decays.
- No indications of CP are observed.
- Fluctuations in p+p and Pb+Pb interactions are similar.
- Results from Ar+Sc interactions are coming soon(!)
Thank you.
Motivation

Several experimental observables proposed to look for CP:
- Fluctuations of mean transverse momentum and multiplicity;
- Pion-pion intermittency analysis;
- Elliptic flow of baryons and mesons;
- Transverse mass spectra of baryons and anti-baryons.

**Fluctuations are:**
- tool to study the properties of onset of deconfinement (OD) and different phases
  - density irregularities (bubbles), difference between fluctuations in QGP and hadron phase, e.g. charge, baryon-to-strangeness fluctuations
- basic signal of the critical point (CP)
  - the characteristic length scale of the structure of the physical system, also known as the correlation length $\xi$, becomes infinite

Non-statistical fluctuations are difficult to measure due to, e.g.:
- limited acceptance of measurements
- contribution of fluctuations coming from final-state interactions and resonance decay
<table>
<thead>
<tr>
<th>Beam momentum [GeV/c]</th>
<th>$\sqrt{s_{NN}}$ [GeV]</th>
<th>p+p</th>
<th>Be+Be</th>
</tr>
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<tbody>
<tr>
<td>20</td>
<td>6.3</td>
<td>1.3M</td>
<td>1.2M</td>
</tr>
<tr>
<td>31</td>
<td>7.6</td>
<td>3.2M</td>
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</tr>
<tr>
<td>40</td>
<td>8.7</td>
<td>5.2M</td>
<td>0.9M</td>
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<tr>
<td>80</td>
<td>12.3</td>
<td>4.4M</td>
<td>1.2M</td>
</tr>
<tr>
<td>158</td>
<td>17.3</td>
<td>3.5M</td>
<td>0.9M</td>
</tr>
</tbody>
</table>

**Event selection**

Event selection criteria:
- well defined p+p/Be+Be interaction
- no off-time particles
- centrality selected by forward energy measurements (Be+Be)

**Track selection**

- sufficient number of points in TPCs
- track trajectory points to the interaction point
- no $e^+ / e^-$
- $p_T < 1.5$ GeV/c

p+p, C+C, Si+Si and Pb+Pb interactions, used for comparison, were measured by the NA49 experiment.
Non-target interactions
In order to correct the data for non-target interactions, NA61/SHINE acquires data of both target-inserted and target-removed collisions. Then, in the analysis procedure, non-target interactions are subtracted.
Example of z position distribution of the fitted vertex for Be+Be at 150 GeV/c:

Detector effects
Corrections for detector effects are estimated to be small but still under investigation.
Chemical fluctuation analysis

- Presented results were obtained from \( p+p \) data collected in 2009 by NA61/SHINE at \( \sqrt{s_{NN}} = 7.6 - 17.3 \text{ GeV} \)
  - \( p+p \) at 17.3 GeV - 4.0M events
  - \( p+p \) at 12.3 GeV - 5.0M events
  - \( p+p \) at 8.7 GeV - 5.8M events
  - \( p+p \) at 7.6 GeV - 3.5M events

- Event and track cuts were chosen to select only inelastic interactions with particles produced in strong and EM processes within the NA61/SHINE acceptance.

- Analysis focuses on fluctuations of \( \pi = \pi^+ + \pi^- \), \( K = K^+ + K^- \) and \( p + \bar{p} \) as well as positively charged hadrons \( (p, K^+, \pi^+) \) by getting first and second (pure and mixed) moments of identified particle multiplicity distributions.

- Second moments of identified particle multiplicity distributions are corrected for the misidentification effect using the identity method \(^1\).

- Presented results of NA61/SHINE include statistical errors and first estimate of systematic uncertainties (work to finalize systematic uncertainties is in progress e.g. feed down and detector effects).

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\(^1\) PRC83:054907, PRC84:024902, PRC86:044906
Particle identification in NA61/SHINE

Particle identification for chemical fluctuation analysis is based on dE/dx measurements in relativistic rise region.

Inclusive dE/dx spectra is sliced in $p_{tot}, p_T$ bins.

A sum of Gaussian functions is fitted in each phase-space bin.
Identity method - single particle identity

The identity method allows to obtain second and third moments (pure and mixed) of identified particle multiplicity distribution corrected for misidentification effect.

A particle identity is calculated as:

$$w_i = \frac{\rho_i(dE/dx)}{\rho(dE/dx)},$$

where $\rho_i$ - function fitted to $i^{th}$ particle type and $\rho$ - function fitted to total dE/dx distribution in a given phase-space bin.

Example of $w_\pi$ distribution for p+p at 12.3 GeV.
Identity method - event identity measure

Event quantity $W_i$ defined as:

$$W_i = \sum w_j,$$

where summation runs over all particles in an event.

Once, detector response ($\rho_i$) and $W$ distributions are known the identity method is used to obtain moments of identified particle multiplicity distributions.
Correction for detector effects

Corrections for detector effects were calculated using EPOS model as the ratio of generated tracks and the reconstructed tracks.

\[
\text{Corr}(\Delta \eta, \Delta \phi) = \frac{MC_{\text{pure}}(\Delta \eta, \Delta \phi)}{MC_{\text{rec}}(\Delta \eta, \Delta \phi)}
\]

For both data and simulation NA61 detector acceptance was applied. Data correction is done by multiplying each bin in uncorrected data distribution with the corresponding bin in corrections distribution of detector effects.

\[
C(\Delta \eta, \Delta \phi) = C^{\text{raw}}(\Delta \eta, \Delta \phi) \cdot \text{Corr}(\Delta \eta, \Delta \phi)
\]
Energy dependence of two particle correlations - all charged

The enhancement "saddle" at (0, 0) rises with increasing beam momentum.
Energy dependence of two particle correlations - unlike sign

The enhancement at \((0, 0)\) rises with increasing beam momentum.
Influence of $p_T$ cut

**DATA**

- 158 GeV/c, all charged, $p_T < 1.5$ GeV/c
- 158 GeV/c, all charged, full $p_T$ spectrum

**EPOS**

- 158 GeV/c, all charged, $p_T < 1.5$ GeV/c
- 158 GeV/c, all charged, full $p_T$ spectrum

- EPOS in qualitative agreement with the data
- no influence of $p_T$ cut
- no jets at top SPS energy
$C(\Delta \eta, \Delta \phi)_{\text{data}} / C(\Delta \eta, \Delta \phi)_{\text{EPOS}}$

All charged

6.3 GeV

17.3 GeV

Unlike-sign

MMP, WUT (NA61/SHINE)  Quark Matter 2015, Kobe, Japan 28-09-2015 29 / 26
NA61/SHINE and energy - system size scan

The ion program of the NA61/SHINE experiment aims to study the onset of deconfinement and search for the critical point indicated by the NA49 experiment.

In order to achieve this goals it performs system size - energy scan at the SPS accelerator with p+p and A+A interactions.
System size and its fluctuations

In comparison of p+p to A+A interactions the **system size** is the main difference. As in A+A collisions, it is not possible to fix system size and there are always some **fluctuations of it**.

There are several models which address it directly, e.g.:

**Wounded Nucleon Model**

- **A+A collision** - **Incoherent composition of the collisions of individual nucleons** (participants)

- **Participants** which collided inelastically at least once are called wounded nucleons,

- **Particles** from each wounded nucleon are produced independently as in nucleon-nucleon collision.

**Independent Particle Production Model**

\[
P_N(\alpha_1, \beta_1, \ldots, \alpha_N, \beta_N) = P_N \times P_{\alpha_1} \times \ldots \times P_{\alpha_N} \times P_{\beta_1} \times \ldots \times P_{\beta_N},
\]

where \(P_N\) is an arbitrary multiplicity distribution of particles. E.g. ideal Boltzmann gas model in the Grand Canonical Ensemble formulation.
Features of p+p interactions and goals of this thesis

p+p interactions allow for establishing contribution of

- conservation laws,
- resonance decays, and
- detector acceptance.

But, their specific features should be accounted

- the log-normal shape of the distributions
- the KNO-G scaling
- the average multiplicity obeys a power law
Goals of this analysis were:

- to establish and test method allowing to analyse identified hadron fluctuations in p+p and A+A interactions - the **identity method**

- to analyse **fluctuations of identified hadrons** in p+p interactions

- to compare obtained results with **models predictions and Pb+Pb collisions**
Particle Identification

Particles are identified using their measured charge, momentum and mass. The last is measured indirectly via e.g. energy loss in time projection chambers.

\[ \frac{dE}{dx} = K Z^2 \frac{Z}{A} \frac{1}{\beta^2} \cdot \left[ \frac{1}{2} \ln \frac{2me^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} \right] - \beta^2 - \frac{\delta(\beta \gamma)}{2} \]

The energy loss of a charged particle in the detector gas is described by the Bethe-Bloch formula.

Slice in charge, \( p \) and \( p_T \):

This formula does not allow for identification particle by particle.

Thus, instead of tagging particles with...
Particle identity

i.e. probability of being of a given type:

\[ w_i = \frac{\rho_i(dE/dx)}{\rho(dE/dx)}, \]

where \( \rho_i \) - function fitted to \( i^{th} \) particle type and \( \rho \) - function fitted to total \( dE/dx \) distribution in a given phase-space bin.

Particle identity

i.e. probability of being of a given type::

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where \( \rho_i \) - function fitted to \( i^{th} \) particle type and \( \rho \) - function fitted to total \( dE/dx \) distribution in a given phase-space bin.

example for p+p at 12.3 GeV

the left particle:  
\[ w_\pi = 0; \quad w_p = 0.8 \]

the middle particle:  
\[ w_\pi = 0.8; \quad w_p = 0 \]

allows to obtain second and third moments (pure and mixed) of identified particle multiplicity distribution corrected for misidentification effect.

Once, detector response ($\rho_i$) and $W$ distributions are known the identity method is used to obtain moments of identified particle multiplicity distributions. $\rho_i, W_i, \ldots \rightarrow < N_i^2 >, < N_i,j >$

Event identity

Particle identity is a probability of being of a given type thus sum of $w_i$ over all particles in an event gives mean multiplicity:

$$W_i = \sum_{j=0}^{j=N} w_i,$$

where $j$ is particle index in an event.
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Sum of Gaussian functions is fitted in each phase-space bin.