News from fluctuation and correlation analysis from NA61/SHINE at the CERN SPS

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1. May serve as a signature of the onset of deconfinement (OD)
Close to the phase transition Equation of State changes rapidly which can impact energy dependence of fluctuations

2. Can help to locate the critical point of strongly interacting matter (CP)
Analogy to critical opalescence – enlarged fluctuations close to the critical point. For strongly interacting matter maximum of CP signal expected when freeze-out happens near CP

http://www.msm.cam.ac.uk/doitpoms/tlplib/solid-solutions/videos/laser1.mov
NA61/SHINE detector layout

Unique, multi-purpose facility to study hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN SPS

Large acceptance fixed target spectrometer exposed to primary (ions) and secondary (ions, hadrons) beams
Motivation of the NA61/SHINE strong interaction programme

p+p and \(^{7}\text{Be}+^{9}\text{Be}\) results to be shown in this presentation
Two-particle correlations in \( p+p \) - motivation

Two-particle correlations in \( \Delta \eta, \Delta \phi \) intervals.

- Studied extensively at RHIC and LHC.
- This method allows to disentangle different sources of correlations:
  - jets,
  - flow,
  - resonance decays,
  - quantum statistics effects,
  - conservation laws.

The motivation
To study the sources of correlations at SPS, in the fixed target NA61 experiment.
Two-particle correlations in p+p - definitions

Correlations are calculated by finding the difference in pseudo-rapidity and azimuthal angle between two particles in the same event.

\[ \Delta \eta = |\eta_1 - \eta_2| \quad \Delta \phi = |\phi_1 - \phi_2| \]

The azimuthal angle is folded (to improve statistics): if \( \Delta \phi > \pi \) then \( \Delta \phi = 2\pi - \Delta \phi \).

**Correlation function:**

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

\[
S(\Delta \eta, \Delta \phi) = \frac{d^2 N^{\text{signal}}}{d\Delta \eta d\Delta \phi} \quad M(\Delta \eta, \Delta \phi) = \frac{d^2 N^{\text{mixed}}}{d\Delta \eta d\Delta \phi}
\]

Correlation function ratio is calculated and normalized in restricted region: \( 0 < \Delta \eta < 3 \).

Event and track cuts were chosen to select only inelastic interactions with particles produced in strong and EM processes within the NA61/SHINE acceptance. The results are corrected on detector effects: tracking inefficiencies, trigger bias.
Two-particle correlations in p+p - structures

- Maximum at \((\Delta \eta, \Delta \phi) = (0, \pi)\) - probably resonance decays and momentum conservation.
  - the strongest in unlike-sign pairs,
  - still visible in positively charged pairs (\(\Delta^{++}\) decay),
  - non-visible in negatively charged (almost no double-negative resonances).

- An enhancement at \((0, 0)\) - probably Coulomb or quantum statistics effects.
  - not strong in unlike-sign pairs,
  - clearly visible in same charge pairs.
Two-particle correlations in p+p – NA61 vs ALICE, energy dependence

$\sqrt{s_{NN}} = 6.3$ GeV

$\sqrt{s_{NN}} = 17.3$ GeV

Resonance decay hill is more visible at lower energies.
Jets dominate at higher energies.
Two-particle correlations in $p+p$ – $C(0,0)$ in NA61 and ALICE

$C(0,0)$ and $C(0,\pi)$ in dependence of energy show monotonical behaviour. $C(0,0)$ rises with energy whereas $C(0,\pi)$ decreases with energy.
Two-particle correlations in $\Delta \eta$, $\Delta \phi$ – a unique tool to test models

EPOS and UrQMD are with NA61 acceptance; all charged particles

Qualitative agreement of NA61 results with predictions of EPOS
Transverse momentum and multiplicity fluctuations - motivation

(search for the Critical Point signal in fluctuations)

NA49 blazed a trail...

System-size scan with p, C, Si, and Pb beams at 158 GeV/c revealed an increase of fluctuations for medium-size systems, consistent with CP predictions

NA61/SHINE goes further...

2D energy–system size scan is expected to give more insight into the CP location
Transverse momentum and multiplicity fluctuations – measures

The most natural way to describe fluctuations of a quantity $A$ is to use an intensive quantity, scaled variance:

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

However, in GCE, scaled variance can be expressed as:

$$\omega[A] = \omega[\alpha] + \bar{\alpha}\omega[V]$$

thus $\omega[A]$ depends on the volume fluctuations via $\omega[V]$.

Measures independent of the unavoidable fluctuations from collision geometry must be used...
Transverse momentum and multiplicity fluctuations – measures

Two families of strongly intensive quantities

\[
\Delta[P_T, N] = C^{-1}_\Delta \left[ \langle N \rangle \omega[P_T] - \langle P_T \rangle \omega[N] \right]
\]
\[
\Sigma[P_T, N] = C^{-1}_\Sigma \left[ \langle N \rangle \omega[P_T] + \langle P_T \rangle \omega[N] - 2 \langle \langle P_T N \rangle - \langle P_T \rangle \langle N \rangle \rangle \right]
\]

\[P_T = \sum_{i=1}^{N} p_{Ti}\]

- independent of the volume and the volume fluctuations in GCE
- \(\Delta[P_T, N] = \Sigma[P_T, N] = 0\) in the absence of fluctuations
- normalization factors chosen such, that
  - both quantities are dimensionless
  - \(\Delta[P_T, N] = \Sigma[P_T, N] = 1\) for the Independent Particle Model


For comparison with NA49

\[
\Phi_{P_T} = \sqrt{p_T \omega[p_T]} \sqrt{\Sigma[P_T, N] - 1}
\]
Transverse momentum and multiplicity fluctuations – energy dependence
Transverse momentum and multiplicity fluctuations – energy dependence

- No structures which could be related to the CP in p+p, nor in Be+Be
- Weak (if any) dependence of centrality in Be+Be
- Be+Be results close to p+p
- Bose-Einstein and/or PT/N – N anticorrelations probably responsible for Δ and Σ difference
Transverse momentum and multiplicity fluctuations – comparison with NA49

It is impossible to correct fluctuations for the acceptance, therefore to compare the $\Phi_{\rho T}$ results, NA49 cuts have been applied to the NA61/SHINE data.

In NA49 because of high density of tracks, analysis was limited to forward rapidity region $(1.1 < y_\pi < 2.6)$

**System size scan:**

Both NA61/SHINE Be+Be and p+p consistent with the dependence suggested by NA49
Charge fluctuations of non-identified particles

New strongly intensive measures $\Delta$ and $\Sigma$ (here applied to $N_+, N_-$ fluctuations) → PR C88, 024907 (2013)

\[
\Delta[N_+, N_-] = (\langle N_- \rangle - \langle N_+ \rangle)^{-1}[\langle N_- \rangle \omega[N_+] - \langle N_+ \rangle \omega[N_-]]
\]

\[
\Sigma[N_+, N_-] = (\langle N_- \rangle + \langle N_+ \rangle)^{-1}[\langle N_- \rangle \omega[N_+] + \langle N_+ \rangle \omega[N_-]
- 2(\langle N_+N_- \rangle - \langle N_+ \rangle \langle N_- \rangle)]
\]

$\Delta[N_+, N_-]$ and $\Sigma[N_+, N_-]$ analysis
9 pseudorapidity intervals
$\delta\eta = 0.2 + 0.4 \cdot i \quad i \in [0,8]_{\mathbb{Z}}$

Can be sensitive to electric charge conservation effect and resonance decays.

The analysis of $\Delta[N_F,N_B]$ and $\Sigma[N_F,N_B]$ (left-right fluctuations) in NA61 is ongoing
\( N_+ \) and \( N_- \) fluctuations in Be+Be collisions at 150A GeV/c

- \( \Delta[N_+, N_-] \) and \( \Sigma[N_+, N_-] \) almost independent of centrality.
- Both \( \Delta[N_+, N_-] \) and \( \Sigma[N_+, N_-] \) smaller than 1 (possibly due to energy-momentum conservation and charge conservation effects).
- \( \Sigma[N_+, N_-] \) decreases significantly with growth of \( \delta \eta \).
- Tendency reproduced by EPOS (perfect agreement for \( \Sigma[N_+, N_-] \)).

Systematic errors were estimated to be less than 5% for all points.
Summary

- Two-particle correlations in $\Delta \eta$, $\Delta \varphi$ intervals in inelastic p+p collisions were measured by the NA61/SHINE experiment. Models do not reproduce it.

- Results on transverse momentum and multiplicity fluctuations for p+p and $^7$Be + $^9$Be were presented.

- No sign of the critical point.

- CP discovery waits for Ar+Sc, which will be presented soon...
Additional slides
Physics program

1. Strong interactions program
   a) **search for the critical point of strongly interacting matter**
   b) **study of the properties of the onset of deconfinement**
   c) **study high $p_T$ particles production (energy dependence of nuclear modification factor)**

2. Hadron-production measurements for neutrino experiments
   a) reference measurements of $p+C$ interactions for the T2K experiment
      for computing initial neutrino fluxes at J-PARC

3. Hadron-production measurements for cosmic ray experiments
   a) reference measurements of $p+C$, $p+p$, $p+C$, and $K+C$ interactions
      for cosmic ray physics (Pierre-Auger and KASCADE experiments)
      for improving air shower simulations
NA61/SHINE Detector

1. Large acceptance: 50%
2. High momentum resolution:
   a) $\sigma(p)/p^2 \approx 10^{-4} \text{ (GeV/c)}^{-1}$ (at full B=9 T m)
3. ToF walls resolution:
   a) ToF-L/R: $\sigma(t) \approx 60\text{ps}$; ToF-F: $\sigma(t) \approx 120\text{ps}$
4. Good particle identification:
   a) $\sigma(dE/dx)/<dE/dx> \approx 0.04$; $\sigma(m_{\text{inv}}) \approx 5\text{MeV}$
5. High detector efficiency: 95%
6. Event recording rate: 70 events/sec

$^7\text{Be}+^9\text{Be}@150\text{A GeV/c}$
Beams for NA61/SHINE

- **Beams at NA61/SHINE:**
  - Secondary
  - Primary
  - **Proton:** 13, 20, 31, 40, 80, 158 A GeV/c
  - **Beryllium:** 13, 20, 30, 40, 75, 150 A GeV/c
  - **Pion:** 158, 350 GeV/c
  - **Argon:** 13, 20, 30, 40, 75, 150 A GeV/c

- **Future beams:**
  - Xenon, Lead: 13, 20, 30, 40, 75, 150 A GeV/c

- **Beam intensity at the NA61/SHINE detector up to** $10^6$
  - **ions per 10 second spill**
Secondary beryllium beam

- Fragmentation target length optimized to maximize the production of the desired fragment
- Double magnetic spectrometer separates fragments according to the selected magnetic rigidity
- Possibility to use a degrader, Cu plate where ions lose energy according to the charge
Centrality selection in ion collisions

- PSD (Projectile Spectator Detector) is located on the beam axis and measures the forward energy $E_F$ related to the non-interacting nucleons of the beam nucleus.
- Cuts on $E_F$ allow to select different event classes.
- Four event classes:
  - 0 - 5%
  - 5 - 10%
  - 10 - 15%
  - 15 - 25%
Two-particle correlations in p+p – all charged pairs, energy dependence

The enhancement “saddle” at (0, 0) rises with increasing beam momentum.
Two-particle correlations in p+p – unlike-sign pairs, energy dependence

The enhancement at (0, 0) rises, like in previous slide, with increasing beam momentum.