Latest results from the NA61/SHINE beam energy scan with p+p and Be+Be collisions

Maja Maćkowiak-Pawłowska for the NA61/SHINE Collaboration
Wartsiaw University of Technology

Outline
● Facility
● Ion program:
  ✔ Study of the onset of deconfinement
  ✔ Search of the critical point of strongly interacting matter
● Summary
  ● For neutrino program see Alexander Korzenev's talk (12:15 Thu)

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Facility

It is a unique multi-purpose detector which allows to measure hadron production in: h+p, h+A, A+A at beam momentum 13A-150A(400) GeV/c

\[ \sigma(p)/p^2 \approx 10^{-4} (GeV/c)^{-1} \]

\[ \sigma(dE/dx) \approx 4\% \]

\[ \sigma(ToF) \approx 100\ ps \]
Strongly interacting matter

The NA49 observation of rapid changes in collision energy dependence of hadron production in heavy ion collisions in comparison to p+p interactions led to:

**NA61/SHINE energy – system size scan**
Evidence of rapid changes in p+p

The NA61/SHINE data suggest that even in inelastic p+p interactions the energy dependence of the $K^+/\pi^+$ and the inverse slope parameter of $K^-$ $m_T$ spectra exhibits rapid changes in the SPS energy range but it is reduced in comparison to Pb+Pb.

In p+p interactions an exact strangeness conservation should be taken into account as number of strangeness carriers < 1.
Challenge for string-resonance models

High precision NA61/SHINE data allows to impose rigorous constraints for Monte-Carlo models.

In general string hadronic models do not describe the p+p data quantitatively.

arXiv:1502.07916
To compare results in system size scan a **precise centrality determination** is needed. **Particle Spectator Detector (PSD)** allows for a precise centrality selection by Forward Energy (FE) event selection.
Width of the rapidity distribution

- \( \sigma_y \) calculated from fit of two symmetrically displaced Gaussians
- \( \sigma_y \) related to speed of sound \( c_s^2 \) („dale‟)
- Smooth, monotonic behaviour with energy
- Non-monotonic behaviour with system size

The isospin asymmetry affects width of the \( \pi^- \) rapidity distribution in p+p and Pb+Pb
but
Be+Be is almost isospin symmetric
Comparison of transverse mass spectra

Ratio of normalized $m_T$ spectra allow to compare shape of the spectra

The beam momentum dependence of the ratio observed in $^7$Be+$^9$Be is not visible in Pb+Pb interactions. The shape of the ratio indicates the presence of radial collective flow in $^7$Be+$^9$Be

$^7$Be+$^9$Be data for 0-15% FE event class

Pb+Pb data for 5% or 7.5% most central collisions
**Two-particle correlations**

Two-particle correlations in $\Delta \eta$, $\Delta \Phi$

- Studied extensively in RHIC and LHC
- Allow to disentangle different sources of correlations:
  - Jets
  - Flow
  - Resonance decays
  - Quantum statistics
  - Conservation laws

Correlations are calculated by finding the difference in pseudo-rapidity and azimuthal angle between two particles in the same event. Next they are normalized using mixed events.

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

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

$$M(\Delta \eta, \Delta \phi) = \frac{d^2 N_{\text{mixed}}}{d \Delta \eta d \Delta \phi}.$$
Resonance decay hill is more visible at lower energies. Jets dominate at higher energies.
Search for the critical point

Fluctuations are the main tool to search for the critical point of strongly interacting matter. But in order to compare results from different systems specific quantities are required.

Fluctuations may give also information on conservation laws, resonance decays, onset of deconfinement and many other (e.g. Phys.Rept.351,161-194; J.Phys.G:Nucl.Part.Phys.42,075101)
Strongly Intensive Quantities

Special combination of extensive quantities (depending on volume in GCE) can be a strongly intensive measure

\[
\Delta[A,B] = \frac{1}{C_\Delta} \left[ \langle B \rangle \omega_A - \langle A \rangle \omega_B \right] \\
\Sigma[A,B] = 1 \frac{1}{C_{\Sigma}} \left[ \langle B \rangle \omega_A + \langle A \rangle \omega_B - 2 \langle AB \rangle - \langle A \langle B \rangle \rangle \right]
\]

They are:
- dimensionless
- independent of volume and volume fluctuations
- normalization chosen such that $\Delta[A,B]$=$\Sigma[A,B]$=1 for independent particle model
- $\Delta[A,B]$=$\Sigma[A,B]$=0 in the absence of fluctuations

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

\[
\begin{align*}
PT &= \sum_{i=0}^{N} p_{Ti} \\
\Phi_{p_T} &= \sqrt{p_T \omega[p_T]} \left( \sqrt{\Sigma[P_T,N]} - 1 \right) \\
\Phi_{ij} &= \sqrt{\langle N_i \rangle \langle N_j \rangle} \left( \sqrt{\Sigma[i,j]} - 1 \right) \frac{N_i + N_j}{N_i + N_j}
\end{align*}
\]
• 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 PT/N-N correlations probably introduce difference between $\Delta$ and $\Sigma$ (PRC 89, 034903)
Comparison with NA49

Fluctuations can not be corrected for the detector acceptance thus results from different reactions has to be compared in the same phase-space region.

New results of the NA61/SHINE are in agreement with dependence observed by the NA49 experiment.
Identified particle fluctuations

- p+p interactions close to Pb+Pb
- no structures which could be connected with CP
- different energy dependence of $\Phi_{\pi K^+}$ in p+p and Pb+Pb (possibly connected to OD)
- $\Phi_{\pi(p\bar{p})}$ dominated by resonance decays and conservation laws
Summary

- data taking for system size – energy scan is well advanced
- observation of rapid changes in \( p+p \) interactions at SPS
- string-hadronic model do not describe \( p+p \) spectra
- no CP signal in \( p+p \) and Be+Be interactions; waiting for Ar+Sc
- fluctuations in \( p+p \) and Be+Be interactions are similar and dominated by conservation laws and resonance decays
- fluctuations in \( p+p \) and Pb+Pb interactions are similar

Thank you
Beams for NA61/SHINE

- Primary ions (13A-158A GeV): argon, xenon, lead
- Secondary ions:
  - Hadrons 13-350 GeV
  - Ions 13A-150A GeV
Single particle spectra in p+p interactions
Lambda spectra

NA61/SHINE results are in agreement with the world data
Centrality selection

- 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 $E_f$ allows to select different centrality classes (we select four centralities).
Assymetry in $\pi^-$ distribution in $^7\text{Be}+^9\text{Be}$

- Fitted: double Gaussian function symmetrically from mid-rapidity (both Gaussians have the same width, but they differ in amplitude)

- Asymmetry decreases from 0.86(0-5%) to 0.97(15-20%)

- Two opposite effects influence asymmetry of the spectra: asymmetric system (small effect) and centrality selection based on projectile spectators (large effect)
Transverse mass spectra of $\pi$-

\[
\frac{1}{m_T - m_\pi} \frac{d^2n}{dydm_T} = A m_T \exp \left( -\frac{m_T}{T} \right)
\]
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.:

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

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

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

**Strongly intensive**

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

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

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

- 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

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

$$p_T = \sum_{i=1}^{N} p_{T_i}, \quad \Phi_{p_T} = \sqrt{\rho_{p_T} \omega[p_T]} \left[ \sqrt{\Sigma[p_T, N]} - 1 \right] \quad \Phi_{ij} = \frac{\sqrt{\langle N_i \rangle \langle N_j \rangle}}{\langle N_i + N_j \rangle} \cdot \left[ \sqrt{\Sigma[i, j]} - 1 \right]$$
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)
Energy dependence of identified particle fluctuations

- identity method (PRC84,024902) used for identification
- $\omega_{p+p} \approx \omega_p < 1$ probably due to baryon number conservation
- $\omega_K > 1$ and $\omega_{K^+} \approx 1$ probably due to strangeness conservation
- increase of $\omega_\pi$ reflects increase of $\omega_{N_{ch}}$ in full phase-space
- $\omega_{\pi^+} < \omega_\pi$ probably due to charge conservations
- popular HIC models describe the data
Energy dependence of identified particle fluctuations

- $\Phi_{\pi(p+\bar{p})}$ and $\Phi_{\pi+p}$ below 0 probably due to conservation laws and resonance decays.
- $\Phi_{\pi K} > 0$ probably due to strangeness conservation. $\Phi_{\pi^+K^+} \approx 0$ supports this interpretation.
- $\Phi_{(p+\bar{p})K}$ shows very weak energy dependence and crosses 0 at middle SPS energies.
- EPOS and UrQMD model predictions qualitatively describe the data.
- Fluctuations in p+p and Pb+Pb interactions are comparable.
- $\Phi_{\pi K}$ in p+p interactions increases with energy whereas in Pb+Pb interaction it is not.
- In p+p interactions $\Phi_{(p+\bar{p})K}$ weakly increases with energy whereas in Pb+Pb interactions it decreases with energy. In both reactions it crosses 0 at the same energy.
- UrQMD model describes energy dependence in p+p and Pb+Pb interactions except $\Phi_{(p+\bar{p})K}$ in Pb+Pb.
- similar tendency of $\Phi_{\pi+p}$ in p+p and Pb+Pb
- in p+p interactions $\Phi_{\pi+K^+}$ weakly increases with energy whereas in Pb+Pb interactions it decreases with energy
- UrQMD model does not describe $\Phi_{\pi+K^+}$ and $\Phi_{pK^+}$ in Pb+Pb at low SPS energies
Charged pion fluctuations

B. Maksiak, CPOD (2014)

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