Search for critical effects in NA61/SHINE

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8th International Conference on New Frontiers in Physics
August 21-29 2019
In this presentation...

Introduction to the NA61/SHINE experiment

Onset of deconfinement
   Study of the onset of deconfinement in single particle spectra
   Study of the onset of deconfinement in directed flow observation

Onset of fireball
   Observation of the onset of fireball in particle production properties

Search for critical point
   Search for critical point in particle production properties

Summary and outlook
NA61/SHINE – fixed target experiment at the CERN SPS

• Ion and hadron beams, $p_{\text{beam}} = 13A - 150A$ GeV/c (400 GeV/c)
• Full coverage of the forward hemisphere, down to $p_T = 0$
• Centrality selection based on forward energy measured in PSD
2D phase-space scan by NA61/SHINE

NA61/SHINE experiment performs 2D scan in collision energy and system size to study the phase diagram of strongly interacting matter in baryon density and temperature.

Main goals:
- study of threshold behaviour in HRG-QGP transition: → onset of deconfinement → onset of fireball
- search for the critical point

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Methodology
Event selection based on forward energy measurements

- **Event (centrality) selection** in nucleus-nucleus collisions is done using the measured forward energy ($E_F$) dominated by energy of projectile spectators.

- It does not bias fluctuation studies and it is one of the best ways to restrict event-by-event volume fluctuations on the detector level.

- Intervals in $E_F$ allow to select different centrality classes.

- Examples of event selection using $E_F$ for Ar+Sc:

  ![Graphs showing event selection based on forward energy measurements](image)
Charged particle identification and spectra

Measured $dn/dy$ yields ($\approx 99\%$) are extrapolated beyond the analysis acceptance.

$$dn/dy = \frac{A}{\sigma_0 \sqrt{2\pi}} \exp\left(-\frac{(y-y_0)^2}{2\sigma_0^2}\right) + \frac{A}{\sigma_0 \sqrt{2\pi}} \exp\left(-\frac{(y+y_0)^2}{2\sigma_0^2}\right)$$

$$\frac{d^2n}{dp_T dy} = \frac{Sp_T}{T^2 + Tm_K} \exp \left(-\sqrt{\frac{p_T^2 + m_K^2}{T}}\right)$$

$\text{Be+Be at 40A GeV/c}$
Study of the onset of deconfinement in single particle spectra
Onset of deconfinement: STEP

Plateau – **STEP** – in the energy dependence of the inverse slope parameter $T$ of $m_T$ spectra in Pb+Pb collisions observed at SPS energies. This is expected for the onset of deconfinement due to mixed phase of HRG and QGP (*Statistical Model of the Early Stage*).

Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions.

Magnitude of $T$ in Be+Be slightly higher than in p+p.

Ar+Sc results between p+p/Be+Be and Pb+Pb results.
Onset of deconfinement: HORN

Rapid changes in the energy dependence of the $K^+/\pi^+$ ratio – HORN – were observed in Pb+Pb collisions at SPS energies. This was predicted (SMES) as a signature of onset of deconfinement.

Plateau like structure visible in p+p
Be+Be close to p+p
Ar+Sc is higher than p+p but the energy dependence is similar to p+p (no horn)
Onset of deconfinement: p+p results

Rates of increase with energy of the $K^+ / \pi^+$ ratio and $T$ change sharply in results from p+p interactions at SPS energies.

The fitted change energy is $\approx 7$ GeV – close to the energy of the onset of deconfinement $\approx 8$ GeV.

Resonance-string model (UrQMD) fails to reproduce data.
Study of the onset of deconfinement in directed flow observation
Directed flow and the onset of deconfinement

Directed flow $v_1$ is considered to be sensitive to 1st order phase transition (softening of EOS).
Expected: non-monotonic behavior (positive→negative→positive) of proton $dv_1/dy$ as a function of beam energy - “collapse of proton flow”

Predictions of hydrodynamical model:

Directed flow measured by NA49
at middle SPS energy
(“anti-flow” of protons at mid-rapidity):
Directed flow as a function of rapidity

Flow coefficients are measured relative to the spectator plane estimated with Projectile Spectator Detector (PSD) → unique for NA61/SHINE

No evidence for the collapse of proton directed flow in semi-central Pb+Pb collisions at 13A GeV/c

Results from Pb+Pb collisions at 30A and 150A GeV/c soon!
Observation of the onset of fireball in particle production properties
Onset of fireball: system size dependence of particle spectra

Rapid enhancement of the $K^+/\pi^+$ ratio with the system size was predicted due to formation of the droplet of strongly interacting matter (SMES).

Experimental results suggest:
- $p+p \approx Be+Be$
- visible change between light and intermediate or heavy systems
- effect manifests in mid-rapidity and full acceptance
Onset of fireball: system size dependence in particle multiplicity fluctuations

Scaled variance defined as:

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

is significantly larger for p+p interactions and central Be+Be collisions than for central Ar+Sc collisions and suggest non-negligible change between light and intermediate systems.

p+p data are corrected for experimental biases, systematic uncertainty \( \sim 0.1 \) [EPJ.C76:635]; 0-1% Be+Be data is uncorrected, experimental bias is \( \sim 10\text{-}15\% \); 0-0.2% Ar+Sc data is uncorrected, experimental bias is \( \sim 5\text{-}7\% \).
Search for critical point in particle production properties
Search for critical point in strongly intensive measures: event-by-event fluctuations

**Intensive** quantities: a ratio of two extensive quantities (\(\sim\) volume) is an intensive quantity e.g.:

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

where \(A\) stands for an extensive event quantity.

In statistical model (IB-GCE) \(\omega_i = \frac{\text{Var}(a)}{\langle a \rangle} + \langle a \rangle \frac{\text{Var}(V)}{\langle V \rangle}\), where \(a\) - particles produced in a system with fixed \(V\)

**Strongly intensive** quantities: special combination of extensive quantities, e.g.:

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

- independent of \(V\) and fluctuations of \(V\)
- normalization chosen such that \(\Sigma[A,B] = 1\) for independent particle model and quantity is dimensionless
- \(\Sigma[A,B] = 0\) in the absence of fluctuations
- note: \(\Sigma\) can be sensitive to several physics effects in different ways

Expected: non-monotonic behavior of CP signatures
Introduction to the NA61/SHINE experiment

Onset of deconfinement

Onset of fireball

Search for critical point

Summary and outlook

Critical point: strongly intensive measures $\Sigma[P_T, N]$

Comparison to NA49 A+A at 158A GeV/c within NA49 two different acceptances

System size dependence of $\Sigma[P_T, N]$ at 150/158A GeV/c: NA49 and NA61/SHINE points show consistent trends

So far there are no prominent structures which could be related to critical point

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Search for critical effects in NA61/SHINE
Critical point: proton intermittency as signal of CP

Critical point as 2\textsuperscript{nd} order phase transition \(\rightarrow\) scale invariance \(\rightarrow\) characteristic dependence of fluctuations on size \(\delta\) of subdivision intervals of momentum space \(\Delta\) (power-law form of correlation function for large distances/small momentum transfer)

- Net protons used as proxy for net baryons (same critical fluctuations)
- Transverse momentum space is partitioned into \(M^2\) cells, \(M^2 = (\Delta/\delta)^2\)
- Second factorial moments \(F_2(M)\) as a function of cell size are defined:

\[
F_2(M) \equiv \left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m-1) \right\rangle
\]

\[
\Delta F_2(M) \equiv F_2^{\text{data}}(M) - F_2^{\text{mixed}}(M)
\]

(\text{background subtraction})

At critical point power law dependence is expected:

\[
\Delta F_2(M) \sim (M^2)^{\varphi_2}
\]

Prediction for intermittency index for critical point: \(\varphi_2 = 5/6\)
**Critical point: proton intermittency in Ar+Sc and Be+Be**

\[ F_2(M^2) \text{ moments are higher in data than in mixed events in} \]

\[ \text{Ar+Sc collisions @ 150A GeV/c.} \]

**Possible hint of the intermittency effect??**

(detailed investigation of significance of this result – in progress)

NA61/SHINE: PoS(CPOD2017) 054

Be+Be, 0-12%
150A GeV/c

No signal visible in Be+Be
Summary and outlook
Summary

- 2D scan in system size and collision energy was completed in 2017 with Xe+La data
- Analysis ongoing for p+p, Be+Be, Ar+Sc, Xe+La and Pb+Pb data
  - No horn in Ar+Sc
  - Unexpected system size dependence: (p+p ≈ Be+Be) ≠ (Ar+Sc ≠ Pb+Pb)
  - No convincing indication of CP, proton intermittency signal in Ar+Sc is under scrutiny
  - Plans to extend NA61/SHINE program with measurements of open charm production in 2021-2024
NA61/SHINE programme for 2021-2024

Open questions:

• What is the mechanism of $\langle c\bar{c} \rangle$ production?
• How does the onset of deconfinement impact $\langle c\bar{c} \rangle$ production?
• How does the formation of quark gluon plasma impact $\langle J/\Psi \rangle$ production?

To answer these questions mean number of charm quark pairs, $\langle c\bar{c} \rangle$, produced in A+A collisions has to be known. Up to now corresponding experimental data does not exist and only NA61/SHINE can perform this measurement in the near future.
Detector upgrade during LS2

Construction of Vertex Detector (VD) for $D^0$, $\bar{D}^0$ decay reconstruction

Replacement of the TPC read-out electronics to increase data rate to 1 kHz

New trigger and data acquisition system

New Time-of-Flight detectors

Upgrade of Projectile Spectator Detector

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Stay tuned!
More results from the NA61/SHINE soon
Directed flow as a function of centrality

NA61/SHINE fixed target setup → tracking and particle identification over wide rapidity range

Flow coefficients are measured relative to the spectator plane estimated with Projectile Spectator Detector (PSD) → unique for NA61/SHINE

Close to mid-rapidity (-0.2<y<0.8):

- slope of pion $v_1$ is always negative
- slope of proton $v_1$ changes sign at centrality of about 50%

Nucl.Phys.A982, 439, 2019
Clear mass hierarchy of $v_2$ - radial flow
Difference between $v_2$ for $\pi^+$ and $\pi^-$ is small

Significant mass dependence of $v_1$
Difference between $v_2$ for $\pi^+$ and $\pi^-$ is sensitive to electromagnetic effects

Energy and system size dependence of the $m_T$ spectra of $\pi^-$

- $m_T$ spectra shape differs significantly between $p+p$ and $A+A$ results
- clear system size dependence with small energy dependence
- the effect possibly associated to transverse collective flow
Example of acceptance maps

- TOP ROW → acceptance map example for $p_{beam} = 19A$ GeV/c
- BOTTOM ROW → acceptance map example for $p_{beam} = 150A$ GeV/c
- acceptance studied with MC simulation
- only region with registration efficiency $\geq 99\%$ selected for fluctuation analysis
Event-by-event fluctuations – model predictions

Fluctuations as a function of momentum bin size

Experimental results

$\Delta F_2$ for mid-rapidity protons at 17 GeV

No signal visible in central Be+Be, C+C, Ar+Sc and Pb+Pb

NA49: EPJC 75 (2015) 587
NA61/SHINE: PoS(CPOD2017) 054
Fluctuations as a function of momentum bin size

Experimental results

\( \Delta F_2 \) for mid-rapidity protons at 17 GeV

A deviation of \( \Delta F_2 \) from zero seems apparent in central Si+Si and mid-central Ar+Sc
Proton intermittency vs background

NA61 Ar+Sc 150, cent.10-15%, pur > 90%

bkg vs NA61 Ar+Sc 150, cent.10-15%, pur > 90%