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Badanie fluktuacji netto ładunku w zderzeniach Ar+Sc przy pędzie wiązki 75
GeV/c

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Streszczenie

Tytuł pracy: Badanie fluktuacji netto ładunku w zderzeniach Ar+Sc przy pędzie wiązki 75 GeV/c

Celem programu jonowego NA61/SHINE jest poszukiwanie punktu krytycznego silnie oddziałującej materii. NA61/SHINE przeprowadza skan diagramu fazowego silnie oddziałującej materii poprzez badanie zderzeń różnej wielkości systemów (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) przy różnych energiach (pęd wiązki w przedziale 13A - 158A GeV/c). Badania przedstawione w tej pracy są ważną częścią tych poszukiwań. Sygnaturą punktu krytycznego jest gwałtowna zmiana fluktuacji w krotności cząstek naładowanych oraz netto ładunku w sąsiedztwie punktu krytycznego. Przedstawione wyniki zostały uzyskane dla zderzeń Ar+Sc przy pędzie wiązki 75A GeV/c.

W pracy obliczono wielkości intensywne (skalowane wariancja, skośność, kurtoza) oraz silnie intensywne ($\Omega[N, E_P]$, silnie intensywne kumulanty) wykorzystując momenty centralne i algebraiczne rozkładów krotności oraz netto ładunku. Przeanalizowano ich zachowanie w funkcji wielkości przedziału centralności zderzenia. Otrzymane wyniki porównano z wynikami p+p NA61/SHINE.

Przeprowadzono analizę niepewności statystycznej, używając metody bootstrap oraz porównano otrzymane oszacowanie z niepewnościami uzyskanymi przy użyciu metody podpróbek. Analiza niepewności systematycznej nie została uwzględniona w tej pracy.

Na podstawie przeprowadzonych badań nie można wyciągnąć wniosków dotyczących obecności punktu krytycznego, gdyż konieczna jest analiza pozostałych energii i systemów.

Słowa kluczowe:

plazma kwarkowo-gluonowa, zderzenia ciężkich jonów, punkt krytyczny, fluktuacje, netto ładunek, wyższe momenty, zmienne silnie intensywne

(podpis opiekuna naukowego)

(podpis dyplomanta)

Abstract

Title of the thesis: Net-charge fluctuation analysis in Ar+Sc interactions at beam momentum 75 GeV/c

The goal of the ion programme of NA61/SHINE experiment is the search of the critical point of strongly interacting matter. NA61/SHINE performs scan of the phase diagram of strongly interacting matter by studying collisions of different size systems (p+p, Be+Be, Ar+Sc, Xe+La, Pb+Pb) at different energies (beam momentum in the range of 13A - 158A GeV/c). Results presented in this thesis are important part of this study. The critical point signature is the rapid change of the multiplicity and net-charge fluctuations in the neighbourhood of the critical point. The analysis was performed for Ar+Sc collisions at beam momentum 75A GeV/c.

In this thesis intensive (scaled variance, skewness, kurtosis) and strongly intensive ($\Omega[N, E_P]$, strongly intensive cumulants) quantities were calculated with the use of central and algebraic moments of multiplicity and net-charge distributions. Their behaviour as a function of the width of centrality bin was analysed. Obtained results were compared with p+p NA61/SHINE results.

The statistical uncertainties were obtained with the use of bootstrap method and compared to uncertainties obtained by using subsamples method. Systematical uncertainties were not included in presented analysis.

No conclusions concerning the critical point presence can be made basing on presented research as the rest of energies and systems has to be analysed as well.

Keywords:

quark-gluon plasma, heavy ion collisions, critical point, fluctuations, net-charge, higher moments, strongly intensive moments

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1.2 Quark-Gluon Plasma

color charges. Quarks carry only one color charge. It is possible to observe only particles which are *color-neutral* (white) hadrons, thus quarks have never been observed as free particles. The potential of strong interaction between quarks can be approximated by the formula:

$$V = -\frac{4}{3} \frac{\alpha_s}{r} + kr, \quad (1)$$

where r - distance, α_s - coupling constant of strong interaction and k - the strength of the linear term. For small distances, the strong potential behaves like the Coulomb potential, but with increasing the distance, the potential strongly confines the quarks into hadrons. The closer the quarks are, the weaker the strong force that confines them, so they start to behave like quasi-free particles. This phenomenon is called asymptotic freedom.

1.2 Quark-Gluon Plasma

Quark-Gluon Plasma (QGP) is a state containing quarks and gluons, which are not confined in single hadrons. Such a state is not possible to gain under normal conditions. Quarks are confined in hadrons and an attempt to extract of a single quark by providing energy to the system ends with the creation of a new pair of quarks. During a collision matter is rapidly squeezed and heated. If energy density is high enough, quarks can be freed from their respective hadrons and propagated in a whole system. After the collision, system expands and cools down. When energy density is low enough hadronization process occurs - quarks and gluons form hadrons. Further cooling and expansion causes chemical freeze-out of the system (the chemical composition of the system is fixed). The system reaches kinetic freeze-out when momenta of all particles are fixed [3].

1.2.1 Signatures of QGP

It is not possible to observe QGP directly. The state, created in heavy ion collisions, has extremely short lifetime and high temperature. The measured signal is created by particles formed during hadronization process from the created system. Nevertheless, it is possible to confirm QGP existence by the analysis of variables insensitive to hadronization process, but sensitive to the QGP stage of the collision. The most popular QGP signatures are:

- Strangeness enhancement

Energy required for the production of strange quark inside QGP is much smaller than for the production of strange hadrons in the hadron gas. Also the decay of the strange quark takes longer than hadronisation process, as it decays via weak processes only. That is why, the strangeness enhancement is considered as the signature of QGP. The effect was observed in experiments on the Super Proton Synchrotron (SPS) at CERN, Switzerland [4].

- Jet quenching

Jets are bunches of particles with high transverse momentum, which are produced at early stage of the collision. Studying the azimuthal angle correlations of jets can provide information about creation of QGP. At Relativistic Heavy Ion Collider (RHIC) it was observed [5], that one of the jets (the away-side

jet) disappears in A+A collisions. It is due to creation of hot and dense medium which suppresses the jet.

- Charmonium suppression

The production of pair of $c\bar{c}$ quarks, which are the components of J/ψ meson, takes place at the early stage of the collision. The Debye screening in the QGP causes suppression of the J/ψ production in heavy ion collisions in comparison to p+p interactions. This effect was observed at SPS, RHIC, and Large Hadron Collider (LHC) experiments [6, 7, 8].

- *kink, horn and step* structures

Statistical Model of the Early Stage (SMES) gives the qualitative and quantitative predictions concerning entropy and strangeness production during the first order phase transition of the strongly interacting matter (onset of deconfinement) in A+A collisions. The structures called *kink, horn* and *step* are predicted [9]. Their presence was confirmed by the NA49 experiment [10].

- *kink* - the ratio of the entropy of the system and the number of participants should increase with the energy of the collision. The slope of this increase should be proportional to the effective number of degrees of freedom in the initial state. In QGP this quantity is larger than in hadron gas, so the slope of the ratio dependence should increase at the onset of deconfinement.
- *horn* - the ratio of the strangeness and the entropy of the system in function of energy of the collision should have the sharp maximum in the region of the onset of deconfinement.
- *step* - according to the hydrodynamic approximation, the temperature in the "pure" confined and deconfined phases should increase with the energy of the collision (more precisely - with the energy density). In the mixed phase the temperature should be independent from the energy and constant. The plateau in the region of the onset of deconfinement is predicted in the dependence of temperature on the energy.

1.3 Phase diagram of strongly interacting matter

The states of strongly interacting matter can be presented on the diagram in the space of thermodynamical parameters, e.g. baryon chemical potential (μ_B) and temperature (T), see Fig.2. The μ_B corresponds to the energy needed to remove or add one baryon to the system. Nuclear matter in normal state is placed on the diagram at $\mu_B \approx 940$ MeV. The dotted line at low temperatures in Fig.2 indicates the first order phase transition between hadron liquid and hadron gas.

1.4 High-energy nuclear collisions

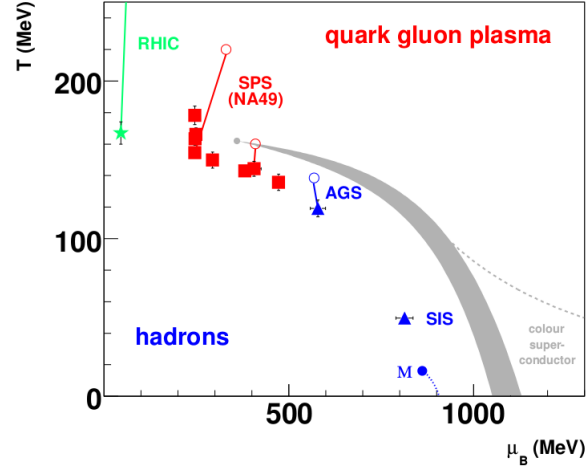


Figure 2: Phase diagram of strongly interacting matter [3]. Open circles denote (hypothetical) points reached just after the collision, closed circles correspond to the chemical freeze-out.

There are two main states of strongly interacting matter: hadron gas and QGP. At high μ_B and low T there is predicted the third state, so-called color super-conductor. According to predictions, this state is present in neutron stars [11]. The phase transition between hadron gas and QGP is the subject of interest of this thesis. The QCD calculations performed on lattice indicates that for $\mu_B = 0$ the crossover between hadron gas and QGP occurs. Crossover is a rapid, but continuous change of the thermodynamical parameters of the system. Such QCD calculations for the higher μ_B are impossible to perform due to their complexity, but for $\mu_B \neq 0$ the, so-called, QCD-inspired calculations were developed [12]. Together with calculations based on models (e.g. [13, 14]), the existence of the first order phase transition between hadron gas and QGP is predicted. The consequence of this prediction is the existence of the critical point (second order phase transition), where the first order line ends. It needs to be stressed, that there are models which do not predict the existence of the critical point [15].

1.4 High-energy nuclear collisions

High-energy collisions of nuclei are a powerful tool to study nuclear matter and to check theory predictions. For last 60 years the accelerators and detectors technology has evolved greatly, allowing to increase the energy of colliding nuclei and to perform more precise measurement.

There are three main accelerators, which provide beams for experiments and which program includes the investigation of the QGP properties or searching for the critical point and investigating the first order phase transition of strongly interacting matter. The biggest one is LHC at CERN, Switzerland with proton energy of 13 TeV in the center-of-mass system. Second one is RHIC in Brookhaven National Laboratory, where maximal collision energy per nucleon pair reaches $\sqrt{s_{NN}} = 200$ GeV. Third is SPS at CERN, which maximal beam momentum is 158A GeV/c for Pb beam and the energy per nucleon pair is $\sqrt{s_{NN}} = 17,3$ GeV. It provides the beam for the NA61/SHINE experiment, which performs energy and system size scan of the phase diagram of strongly interacting matter (NA61/SHINE physics programme is described

in details in Chapter 3). One of the most important discoveries of NA61/SHINE predecessor - NA49, was finding the predicted *kink*, *horn* and *step* structures, what confirms the onset of deconfinement of quarks during the heavy systems collision at SPS energy range (see Fig.3). NA49 results were later expanded by p+p, Be+Be and Ar+Sc collisions from NA61/SHINE. Analysis of these systems showed expected behaviour of Ar+Sc and Be+Be in *kink*. In Ar+Sc for lower energies points are consistent with p+p data and for higher energies - with Au+Au/Pb+Pb data. In Be+Be points are consistent with p+p. Neither p+p nor Be+Be results do not show *horn* structure what means that QGP is not produced in these collisions.

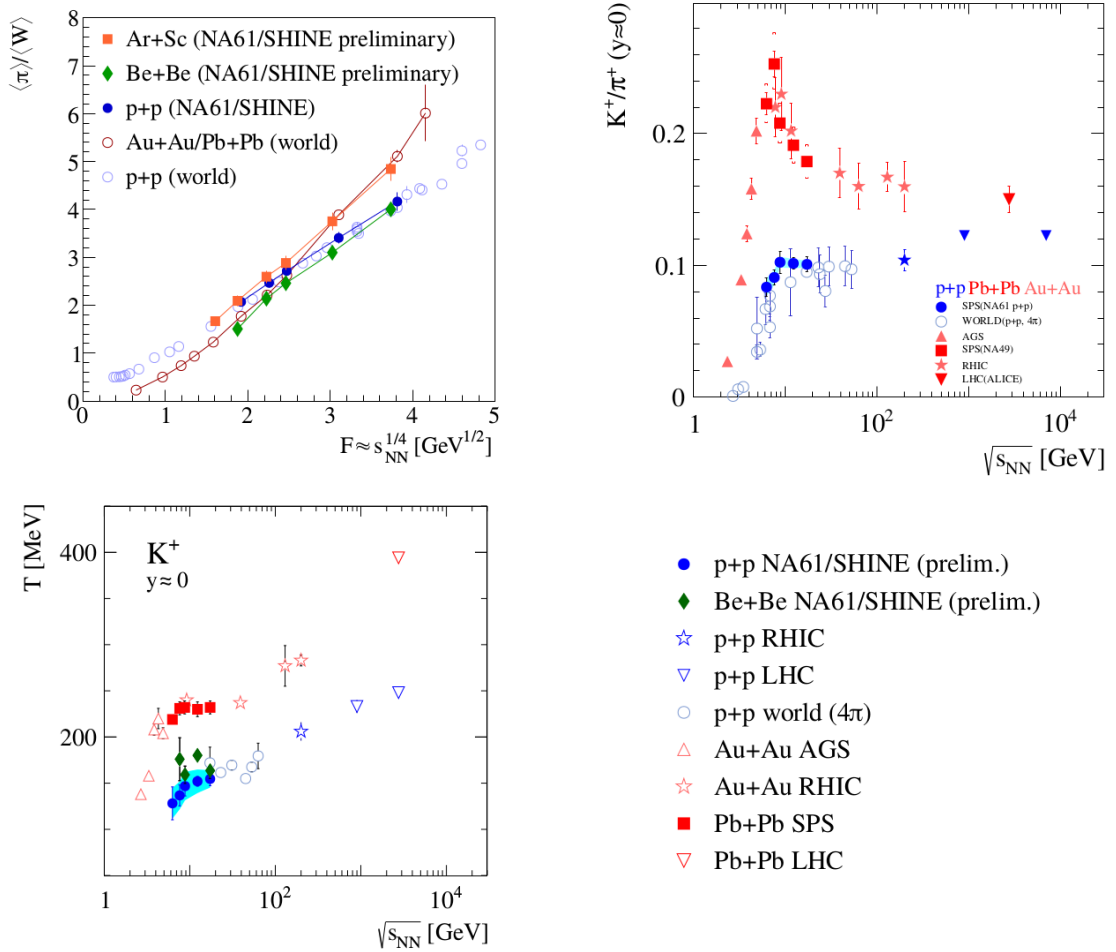


Figure 3: *kink* (top left), *horn* (top right) and *step* (down left) structures predicted by SMES model as the indication of the onset of deconfinement. The results, produced by NA49 on SPS, were confirmed by experiments on RHIC and LHC. In the figure the results from AGS (Alternating Gradient Synchrotron, USA), which were pioneer results, are also presented. Symbol W indicates the number of wounded nucleons (for details see Chapter 2). Symbol T is the inverse slope of m_T (transverse mass) spectrum. [16].

This thesis is a part of the NA61/SHINE strong interactions programme (see Chapter 3). Specifically, the results of this analysis will aid in the search for the critical point.

2 Fluctuations measurement in the Critical Point search

Fluctuations are defined by moments of a given distribution higher than the first moment. They may increase due to finite amount of data or technical limits of the detector. The other possible source of fluctuations are physical processes which happen in the colliding system. Enhanced fluctuations in such observables as multiplicity and transverse momentum are expected in the phase transition between hadron gas and QGP [17]. Explicitly in the critical point the correlation length diverges, what causes the increase of fluctuations signal. This signal can be probed by measuring the event characteristics, such as multiplicity, net-charge or mean transverse momentum from one event to another. Fluctuations measured this way contain fluctuations due to limited statistics and physical phenomena. To reduce the statistical part, the large statistics of data is needed. Fluctuations study for different collision energies and for different system sizes can give the information about nature of the phase transition, in particular about the possible location of the critical point.

2.1 Measures of fluctuations

One of obstacles in fluctuation measurements in heavy ion collisions is the inability to fix the size of the colliding system. Experimentally, it can be limited in centrality¹ classes, where system size still varies from collision to collision. This causes, that the number of participants varies from event to event. In order to compare fluctuations measured in different systems or centralities one requires using quantities independent from the system size and its fluctuations. Such quantities are introduced below.

2.1.1 Intensive quantities

Intensive quantities are the quantities independent from the system size, but dependent on system size fluctuations. They are obtained by dividing two extensive quantities (dependent on the system size), e.g. algebraic (Eq.2) or central (Eq.3) moments of the distribution.

$$\langle N^n \rangle = \sum_N N^n P(N) \quad (2)$$

$$\mu_n = \sum_N (N - \langle N \rangle)^n P(N) \quad (3)$$

The moments can also be described in terms of cumulants (Eq.4).

$$k_2 = \mu_2, \quad k_3 = \mu_3, \quad k_4 = \mu_4 - 3\mu_2^2, \quad \dots \quad (4)$$

The intensive quantities used in this thesis are:

¹Centrality of the collision is defined by the distance between the middle of the collided nuclei (impact parameter). The smaller impact parameter is, the more participants (nuclei, which participated in collision) in the collision and the larger multiplicity. One can obtain events in centrality classes defined in %, where 0% means the most central collisions. Centrality can be estimated with a proper detector, e.g. PSD in NA61/SHINE

Scaled variance:

$$\omega[N] = \frac{\mu_2}{\langle N \rangle} = \frac{k_2}{k_1}, \quad (5)$$

Scaled skewness:

$$S\sigma[N] = \frac{\mu_3}{\mu_2} = \frac{k_3}{k_2}, \quad (6)$$

Scaled kurtosis:

$$\kappa\sigma^2[N] = \frac{\mu_4}{\mu_2} - 3\mu_2 = \frac{k_4}{k_2}, \quad (7)$$

where k_n is the n-th order cumulant and μ_n is the n-th order central moment of a given distribution.

One can distinguish two types of nucleons in a collision:

- the nucleons which do not interact in a collision are called spectators
- the nucleons which interacted inelastically at least once are called wounded nucleons - W (for details see [18])

Wounded Nucleon Model (WNM) proposed by Białaś, Bleszyński and Czyż [19] is one of the simplest models of ion-ion collision. It assumes that particle production in nucleon-nucleus and nucleus-nucleus collisions is an incoherent superposition of particle production from wounded nucleons.

Using WNM, it can be shown, that if W varies according to a certain probability distribution $P(W)$, then $\omega[N]$, $S\sigma[N]$ and $K\sigma^2[N]$ are functions not only of particles produced in a single wounded nuclei, but also of the system size and the system size fluctuations. In this case, the $\omega[N]$, $S\sigma[N]$ and $K\sigma^2[N]$ are given by the following formulas [20]:

$$\omega[N] = \omega[n] + \langle n \rangle \omega[W] \quad (8)$$

$$S\sigma[N] = \frac{\omega[n]S_n\sigma_n + \langle n \rangle \omega[W](3\omega[n] + [n]S_W\sigma_W)}{\omega[n] + \langle n \rangle \omega[W]} \quad (9)$$

$$K\sigma^2[N] = \frac{\omega[n]K_n\sigma_n^2 + \omega[W](\langle n \rangle^3 K_W\sigma_W^2 + \langle n \rangle \omega[n](3\omega[n] + 4S_W\sigma_W + 6[n]S_W\sigma_W))}{\omega[n] + \langle n \rangle \omega[W]}, \quad (10)$$

where the quantities with index n are the quantities from a single wounded nucleon and the quantities with index W characterise the system size change.

If multiplicity distribution from a single wounded nucleon varies according to Poisson distribution, then $\omega[n] = 1$. If there are no fluctuations, $\omega[n] = 0$.

2.1 Measures of fluctuations

2.1.2 Strongly intensive quantities (SIQ)

In order to compare particle production in different systems one wants to ignore the system size fluctuations and focus on particle production from a single wounded nucleon. To remove this unwanted dependence on system size fluctuations, SIQ were introduced. Construction of SIQ requires two extensive event quantities, e.g. multiplicity (N) and another quantity – let's call it B (it can be e.g. energy of participants or sum of transverse momentum).

Example of SIQ are Δ and Σ , defined below:

$$\Delta[N, B] = \frac{1}{\langle B \rangle} (\langle B \rangle \omega[N] - \langle N \rangle \omega[B]) \quad (11)$$

$$\Sigma[N, B] = \frac{1}{\langle B \rangle} (\langle B \rangle \omega[N] + \langle N \rangle \omega[B] - 2cov(N, B)) \quad (12)$$

Linear combination of $\Delta[N, B]$ and $\Sigma[N, B]$ allows to get rid of dependence of B quantity. If N and B are uncorrelated, the scaled variance from a single wounded nucleon can be defined by linear combination of $\Delta[N, B]$ and $\Sigma[N, B]$. Its definition is shown below:

$$\Omega[N, B] = \frac{1}{2} (\Delta[N, B] + \Sigma[N, B]) = \omega[n] \quad (13)$$

One can obtain similar dependencies for higher order moments by using *strongly intensive cumulants* introduced in Ref.[21]. Strongly intensive cumulant of the r -th order (κ_r^*) is presented below:

$$\kappa_r^* = \frac{1}{\mu_{0,1}} \left(\mu_{0,r} - \sum_{i=1}^{r-1} \binom{r-1}{i-1} \mu_{r-i,1} \kappa_i^* \right), \quad (14)$$

where $\mu_{i,j} = \langle N^i B^j \rangle$ is an algebraic moment of i,j -th order of two-dimensional N and B distribution. The form of two first cumulants is:

- $\kappa_1^*[N, B] = \frac{\langle N \rangle}{\langle B \rangle}$
- $\kappa_2^*[N, B] = \frac{\langle N^2 \rangle}{\langle B \rangle} - \frac{\langle N \rangle \langle NB \rangle}{\langle B \rangle^2}$

If N and B are uncorrelated, then:

- $\kappa_1^*[N, B] = \frac{\langle n \rangle \langle W \rangle}{\langle b \rangle \langle W \rangle} = \frac{\langle n \rangle}{\langle b \rangle}$
- $\kappa_2^*[N, B] = \frac{\langle N^2 \rangle}{\langle B \rangle} - \frac{\langle N \rangle \langle NB \rangle}{\langle B \rangle^2} = \frac{\langle n^2 \rangle \langle W \rangle + \langle n \rangle^2 \langle W^2 \rangle - \langle W \rangle^2}{\langle b \rangle \langle W \rangle} - \frac{\langle n \rangle \langle W \rangle (\langle nb \rangle \langle W \rangle + \langle n \rangle \langle b \rangle (\langle W^2 \rangle - \langle W \rangle))}{\langle b \rangle^2 \langle W \rangle^2} =$

$$\frac{\langle n^2 \rangle \langle W \rangle + \langle n \rangle^2 \langle W^2 \rangle - \langle W \rangle^2}{\langle b \rangle \langle W \rangle} - \frac{\langle n \rangle \langle W \rangle (\langle n \rangle \langle b \rangle \langle W \rangle + \langle n \rangle \langle b \rangle (\langle W^2 \rangle - \langle W \rangle))}{\langle b \rangle^2 \langle W \rangle^2} = \frac{\langle n^2 \rangle \langle W \rangle + \langle n \rangle^2 \langle W^2 \rangle - \langle n \rangle^2 \langle W \rangle}{\langle b \rangle \langle W \rangle} - \frac{\langle n \rangle^2 \langle b \rangle \langle W \rangle \langle W^2 \rangle}{\langle b \rangle^2 \langle W \rangle^2} =$$

$$\frac{\langle n^2 \rangle \langle W \rangle - \langle n \rangle^2 \langle W \rangle}{\langle b \rangle \langle W \rangle} = \frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle b \rangle} = \frac{Var[n]}{b}$$

Then a scaled variance from a single wounded nucleon can be obtained by the ratio of these two first cumulants:

$$\omega[n] = \frac{\kappa_2^*}{\kappa_1^*} = \frac{Var[n]}{b} \cdot \frac{\langle b \rangle}{\langle n \rangle} = \frac{Var[n]}{n} \quad (15)$$

By calculating ratios of higher order strongly intensive cumulants one can get intensive quantities from a single wounded nucleon of higher moments of a distribution:

$$S\sigma[n] = \frac{\kappa_3^*}{\kappa_2^*} \quad (16)$$

$$K\sigma^2[n] = \frac{\kappa_4^*}{\kappa_2^*} \quad (17)$$

2.1.3 Scaled variance, skewness and kurtosis at the critical point

There are no predictions of the intensive and strongly intensive quantities at the critical point of strongly interacting matter. Thus expected behaviour of intensive quantities at critical point of nuclear liquid $\leftrightarrow$ gas transition, can be illustrated for the symmetric nuclear matter within Van der Waals equation of state, see Fig.4.

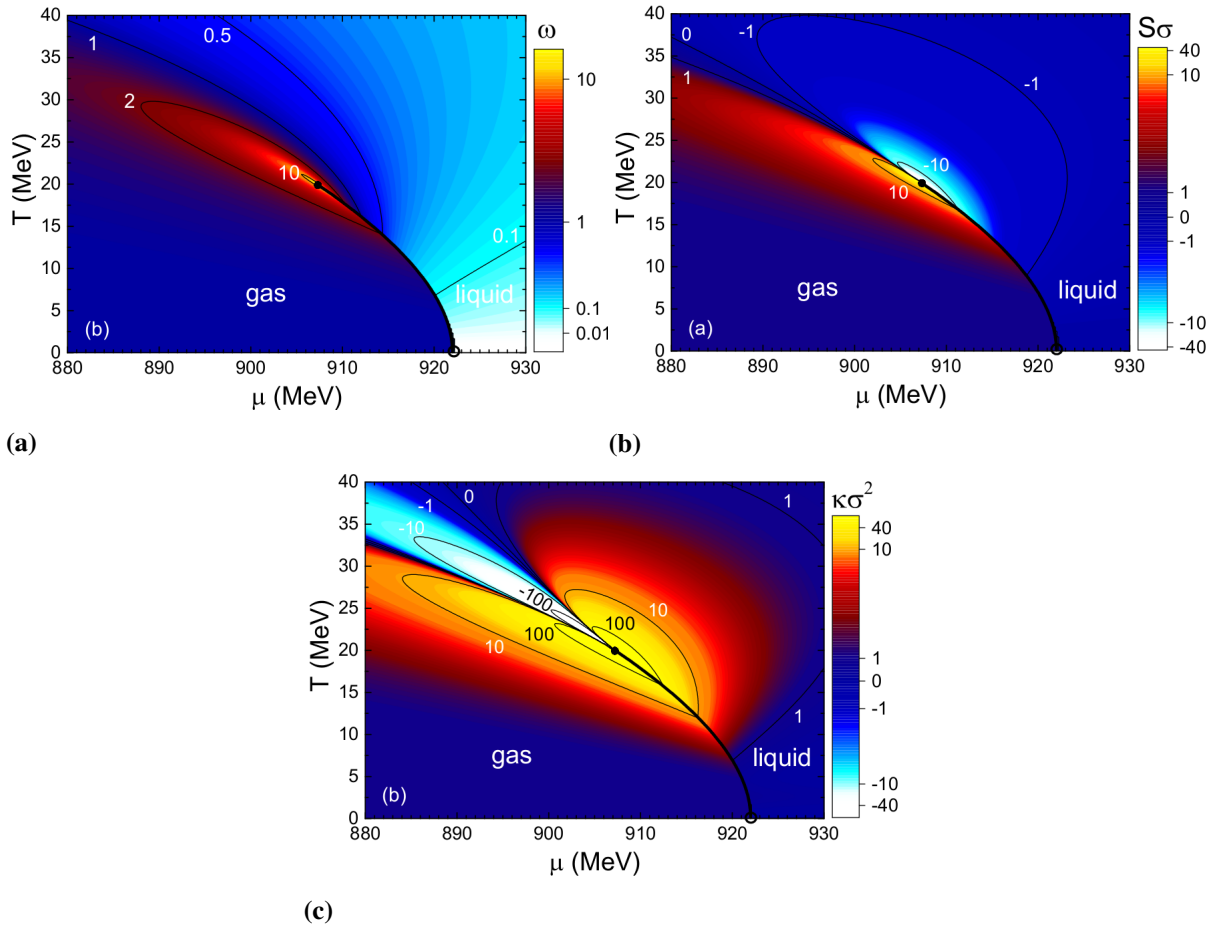


Figure 4: Scaled variance (a), scaled skewness (b) and scaled kurtosis (c) calculated in $[T, \mu_B]$ coordinates within van der Waals equation of state for fermions. The solid circle in the diagram corresponds to the critical point, the open circle at $T=0$ denotes the ground state of nuclear matter [22].

The scaled variance diverges at the critical point and the large values of $\omega[N] \gg 1$ take place along the crossover region. The behaviour of scaled skewness and scaled kurtosis is different. They change

2.2 Multiplicity and net-charge fluctuations in NA49 and NA61/SHINE

values rapidly in the neighbourhood of the critical point, depending on the location on the phase diagram. That is why it is important to investigate moments higher than second in the search for the critical point.

2.2 Multiplicity and net-charge fluctuations in NA49 and NA61/SHINE

2.2.1 Multiplicity fluctuations

Multiplicity fluctuations of positively, negatively and all charged particles were analysed for Pb+Pb, Si+Si, C+C and p+p at different energies by NA49. The analysis of Pb+Pb at two different rapidity intervals: $0 < y_\pi < y_{beam}$ and $1 < y_\pi < y_{beam}^2$, showed decrease of scaled variance of all charged particles and approximately constant behaviour of scaled variance of positively and negatively charged particles, with increasing μ_B (what corresponds to decreasing energy). The results are presented in Fig.5. Clearly, the energy dependence of $\omega[N]$ for Pb+Pb did not show any non-monotonic behaviour which may indicate the critical point presence. Further investigation of collisions of lighter nuclei brought more promising results, see Fig.6. The system size dependence of scaled variance of all charged particles shows a maximum for medium size nuclei.

Due to limited statistics the measured signal is difficult to interpret. One of the goals of NA61/SHINE is to extend these measurements and check available region of phase diagram. One of the extensions is to add measurements of higher order moments which were not measured by NA49.

² y_{beam} is the rapidity of the beam and y_π is the particle rapidity assuming pion mass in center-of-mass system

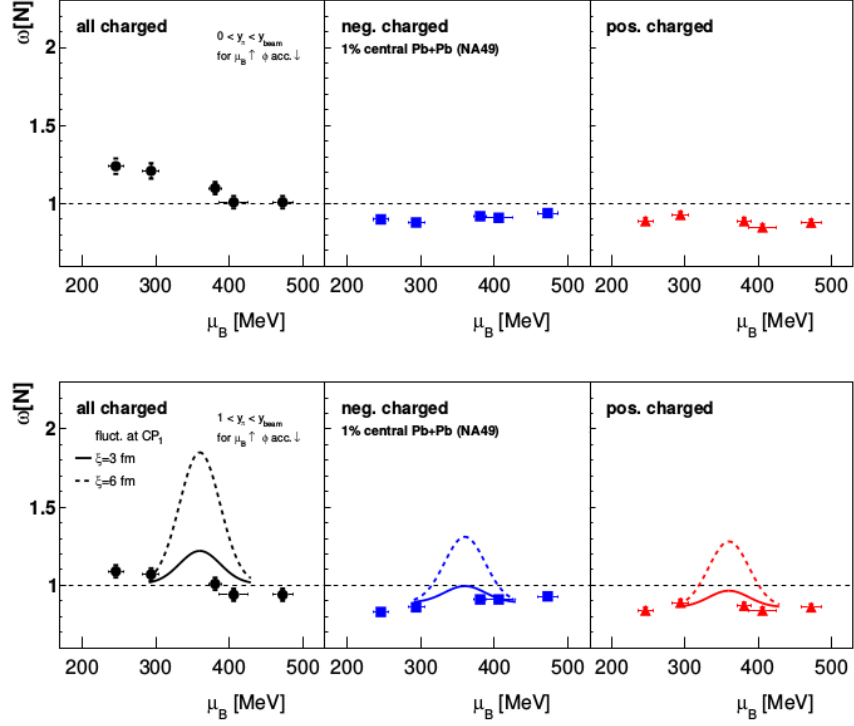


Figure 5: Scaled variance dependence on baryon chemical potential of all charged, negatively charged and positively charged particles produced in 1% most central Pb+Pb collisions at two different rapidity intervals: $0 < y_\pi < y_{beam}$ (top) and $1 < y_\pi < y_{beam}$ (bottom) [23]. Lines correspond to CP predictions [24].

2.2 Multiplicity and net-charge fluctuations in NA49 and NA61/SHINE

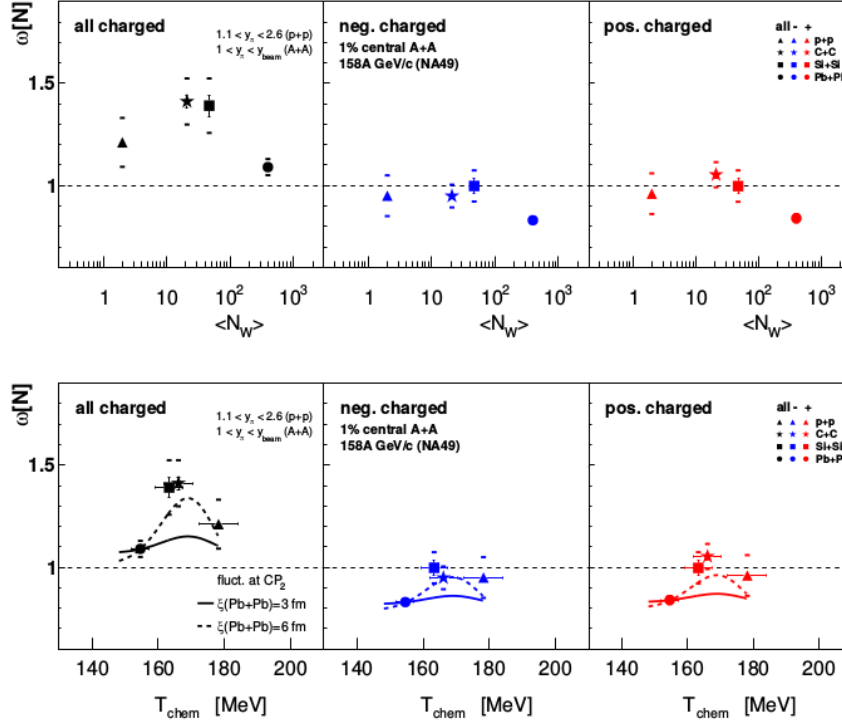


Figure 6: Scaled variance dependence on system size (top) and chemical freeze-out temperature (bottom) of all charged, negatively charged and positively charged particles produced in 1% most central Pb+Pb, Si+Si, C+C collisions and inelastic p+p interactions at 158A GeV [23, 25, 26].

Analysis of the second order moments of multiplicity distributions for Ar+Sc collisions was performed (see [27]). Both scaled variance ($\omega[N]$) and scaled variance from single wounded nucleon ($\Omega[N, E_P]$) were calculated for different energies of collision and centrality 0-0.2% and compared to p+p results. Results are presented in Fig.7. No non-monotonic behaviour was observed as a sign of the critical point presence.

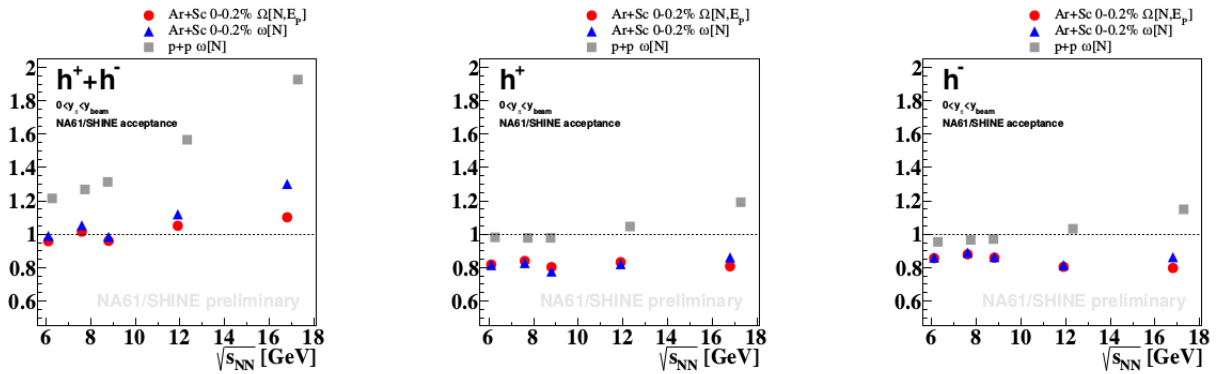


Figure 7: The energy dependences of $\Omega[N, E_P]$ (red dots) and $\omega[N]$ (blue triangles) for 0-0.2% central Ar+Sc collisions compared with $\omega[N]$ for p+p data (grey squares) [27].

Analysis of higher order moments in NA61/SHINE has already started by measuring fluctuations in p+p collisions at different energies (see Fig.8). The multiplicity distributions of negatively charged particles were analysed and compared to EPOS predictions. EPOS is a model which name states for "Energy conserving quantum mechanical multiple scattering approach, based on Partons (parton ladders), Off-shell remnants, and Splitting of parton ladders. It is described in details in [28]. Scaled variance, scaled skewness and scaled kurtosis increase with collision energy in p+p collisions. There are no non-monotonic structures which indicate the presence of the critical point.

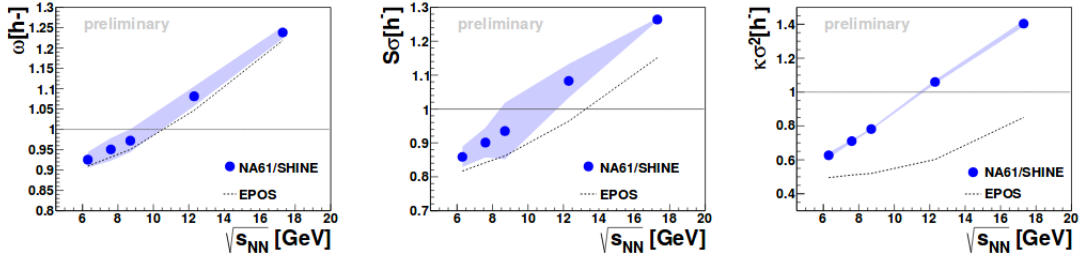


Figure 8: Energy dependence of scaled variance (left), scaled skewness (middle) and scaled kurtosis (right) of negatively charged particles distributions measured in inelastic p+p interactions by NA61/SHINE [29].

2.2.2 Net-charge fluctuations

The scaled variance and higher order moments of net-charge distributions were studied for p+p interactions at different energies by NA61/SHINE experiment. The cumulants of the conserved charge in quantum statistical mechanics are given by derivatives of the grand potential, what allows to connect them with available theoretical models of the critical point [30]. The results are presented in Fig.9 and compared to EPOS model and Skellam distribution³. No indication of the critical point is visible.

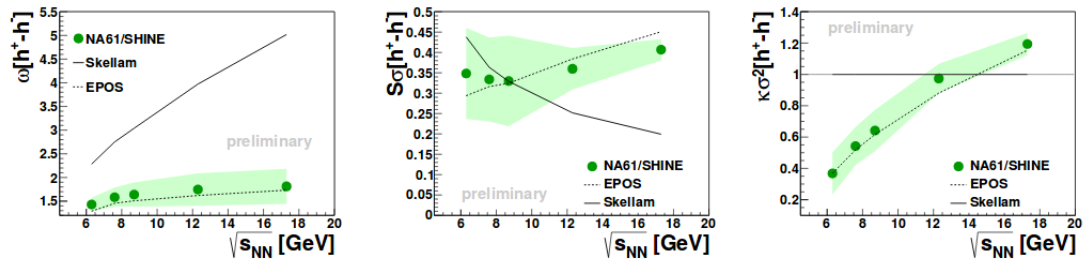


Figure 9: Energy dependence of scaled variance (left), scaled skewness (middle) and scaled kurtosis (right) of net-charged distributions measured in inelastic p+p interactions by NA61/SHINE [29].

³The Skellam distribution is the discrete probability distribution of the difference of two statistically independent random variables, each Poisson-distributed

3 NA61/SHINE experiment

NA61/SHINE is a fixed-target experiment located at CERN in Geneva, Switzerland. It is placed in the North Area. It is a successor of the NA49 experiment, which was operating in 1994 – 2002 and it is using an upgraded apparatus of NA49. The name SHINE stands for **S**PS **H**heavy **I**on and **N**eutrino **E**xperiment.

3.1 Physics programme

The main goal of the NA61/SHINE experiment is to study hadron production in different types of collisions within three programmes:

1. the programme of strong interactions: systems of different sizes at different energies are collided (Fig.10) in order to study properties of the transition between the quark-gluon plasma and hadron gas. In particular the search of critical point of strongly interacting matter and detailed study of onset of deconfinement is performed.
2. the neutrino programme: proton-nucleus interactions are recorded to determine parameters of neutrino beams produced at J-PARC, Japan, and Fermilab, US.
3. the cosmic ray programme: hadron-nucleus interactions are measured in order to improve modelling of cosmic ray showers. This will improve the understanding of the nuclear cascades in the air showers and help to deduce the properties of high-energy cosmic rays from air-shower data.

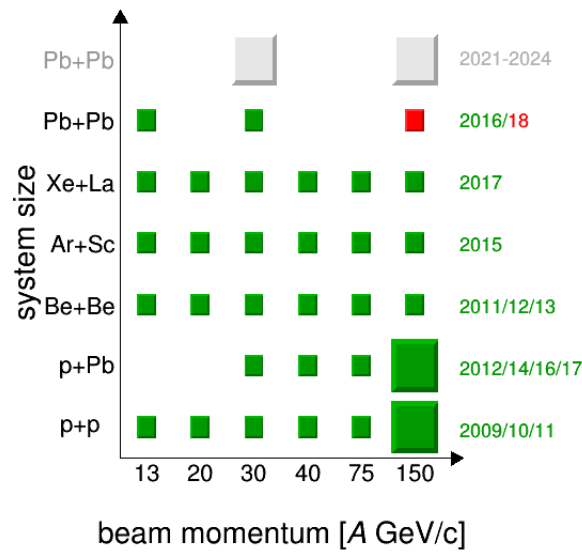


Figure 10: Collided systems and beam momenta in the programme of strong interactions [31].

3.2 Experimental facility

NA61/SHINE is a fixed-target experiment. The experimental set-up is shown in Fig.11. Before the argon ions reached the experimental set-up, they were accelerated in the following CERN accelerators: Linac3, LEIR, PS and SPS. In SPS, ions are accelerated to the required energy, then the beam is de-bunched and extracted to the North Area. Beam position is measured with the use of three Beam Position Detectors (BPDs) and a set of scintillation and Cherenkov counters. Behind the target, there are four large volume Time Projection Chambers (TPCs), which are the main components of the experimental set-up. First two - vertex TPCs (VTPCs) - are placed in a magnetic field of two superconducting dipole magnets. The next two - main TPCs (MTPCs) - are installed behind the magnets, on both sides of the beam. Small GAP TPC which is presented in the scheme in Fig.11 between VTPCs, was not used during Ar+Sc data taking. Behind MTPCs, the Time-of-Flight detector is situated. Information from TPCs and ToF can be used for a particle identification. The furthest detector in the set-up is Projectile Spectator Detector (PSD). It provides an information about the energy deposited by projectile spectators, what is necessary to determine the centrality of the collision. Full description of the experimental facility can be found in Ref.[32].

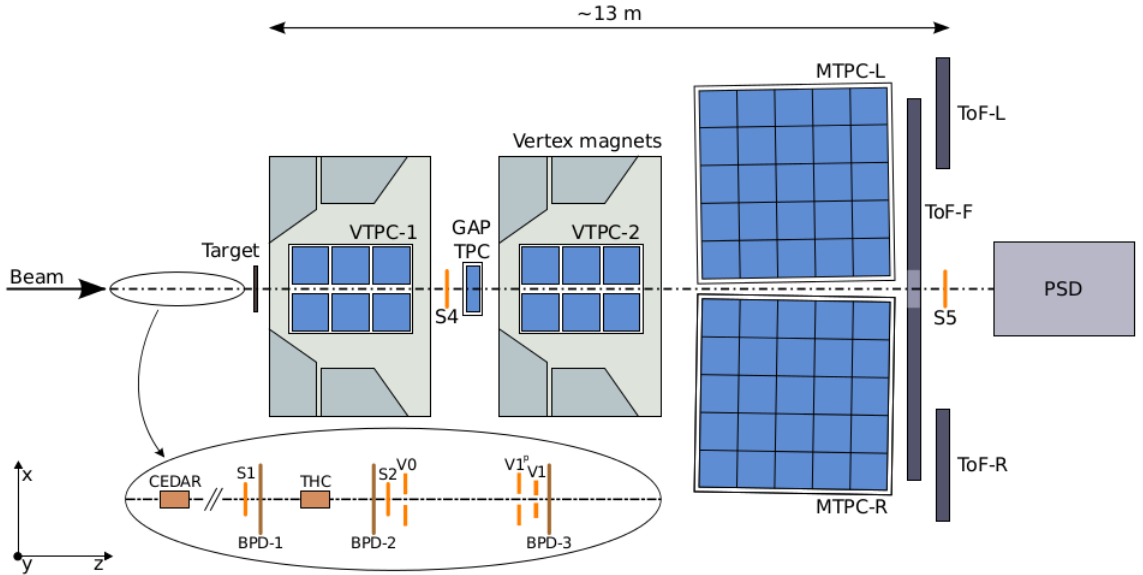


Figure 11: The layout of NA61/SHINE experimental set-up. The enlarged beamline part was used for p+p data taking. Particular parts and detectors are described in the text [32].

3.2 Experimental facility

3.2.1 Beam detectors, counters, triggers

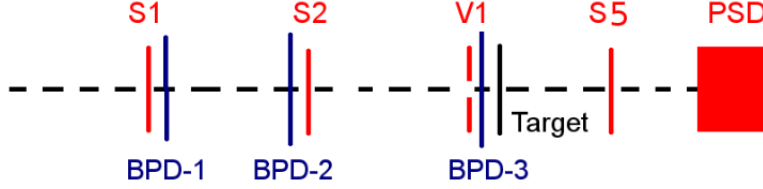


Figure 12: The scheme of beam detectors, counters and triggers during Ar+Sc data taking. The detailed description of the set-up is in the text.

Beam detectors set-up for Ar+Sc data taking is presented in Fig.12. There are three Beam Position Detectors, which are used to measure position of the beam particles in transverse plane. They are placed along the beamline upstream of the target. The detectors are proportional chambers contained Ar/CO₂ 85/15 gas mixture. Each BPD measures the position of the beam particle in two orthogonal directions using two planes of orthogonal strips. BPDs are prepared to measure beams at high-intensity about 10⁵ particles/second.

There are three scintillators: S1, S2, S5 and one veto counter: V1 mounted along the beamline. They provide timing information and are used to define the triggers. For Ar+Sc data taking, four triggers were defined. The trigger logic is presented in Tab.1. The description of the triggers is presented below:

- T1 - identifies beam particles before the target
- T2 - selects the most central interactions, by condition of presence of the beam before the target, disappearing beam behind the target (anticoincidence of the S5 counter) and a threshold on PSD energy
- T3 - detects beam halo
- T4 - minimum bias trigger - selects all interactions with the target (no selection on centrality as in T2 trigger).

Table 1: Trigger logic in Ar+Sc collisions data taking.

Trigger	Configuration
T1	$S1 \times S2 \times \overline{V1}$
T2	$S1 \times S2 \times \overline{V1} \times \overline{S5} \times \overline{PSD}$
T3	$S1 \times S2$
T4	$S1 \times S2 \times \overline{V1} \times \overline{S5}$

3.2.2 Target and beam

For Ar+Sc collisions at beam momentum 75A GeV/c, targets produced in Stanford Advanced Materials were used. The targets were 2 × 2 cm plates of 2 and 4 mm thickness, containing (99.29 ± 1)% of Sc. During the data taking, both plates (2 + 4 mm) were used.

Beam delivered by SPS accelerator contained argon. It was a primary beam prepared specifically for NA61/SHINE.

3.2.3 Time Projection Chambers

Four large volume Time Projection Chambers are the main tracking devices in NA61/SHINE experiment. They allow the measurement of particle energy loss dE/dx . There are two vertex TPCs (VTPCs) and two main TPCs (MTPCs). VTPCs are located in the magnetic field of two superconducting dipole magnets with a maximum total bending power of 9 Tm at currents of 5000 A. The standard configuration for data taking at beam momentum per nucleon of 150 GeV/c and higher is nominally 1.5 T in the first magnet and 1.1 T in the second magnet. When the beam momentum is lower, the magnetic fields are proportionally reduced with keeping the ratio between them constant. This procedure is performed to optimize the geometrical acceptance of the detector. TPCs contain large gas boxes with a gas mixture Ar/CO² in proportion 90/10 and 95/5 for VTPCs and MTPCs respectively. Gas boxes are placed in a homogeneous electric field. Charged particles reaching the TPCs cause ionization of the gas. Electrons, which come from ionization events, drift towards the read-out chambers of TPCs. Placing the VTPCs in magnetic field allows to determine the momentum and sign of the charge of the particle, thanks to bending caused by the Lorentz force.

3.2.4 Time of Flight detector

Three Time of Flight (ToF) detectors: ToF-L, ToF-R and ToF-F were introduced to improve particle identification. The ToF walls are placed behind the MTPCs. Each ToF-L/R walls contains 891 individual scintillation detectors with rectangular dimensions, which have a single photomultiplier tube glued to the short side. The whole surface of the Left and Right wall is 4.4 m². The ToF-F wall contains 80 scintillator bars oriented vertically, which configuration provides a total active area of 720 × 120 cm² and it was not present for Ar+Sc run. The particle's mass squared is obtained by combining the information about the particle's time of flight with the track length and momentum measured in the TPCs. It extends kinematic region where charged particles are identified. The information from ToF detector was not used during the analysis presented in this thesis.

3.2.5 Projectile Spectator Detector

PSD is placed behind the ToF and it is the most downstream detector. It fulfills two roles. First is the determination of centrality of the collision at the trigger level. Second is the measurement of projectile spectator energy in nucleus-nucleus collisions. PSD measurement makes possible the extraction of the number of interacting nucleons from the projectile with the precision of one nucleon. The high energy resolution is important for the fluctuations analysis, because it allows to exclude the part of the fluctuations caused by the variation of the collision geometry. PSD is build from 28 large and 16 small modules, each of them consists of 60 pairs of alternating lead (16 mm) and scintillator (4 mm) tiles sandwiched perpendicular to the beam. PSD scheme, as well as single PSD module scheme are presented

3.2 Experimental facility

in Fig.13.

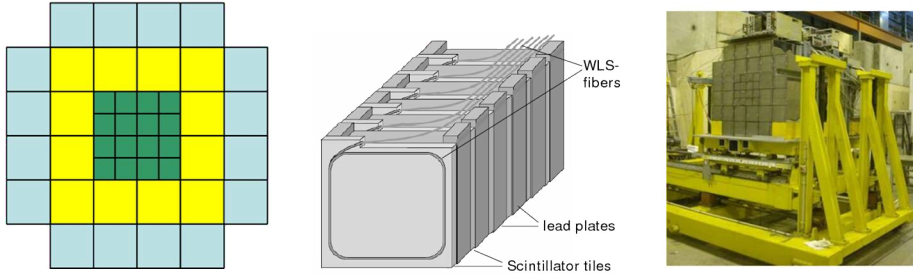


Figure 13: Left: PSD front scheme, middle: single module scheme, right: photo of the PSD [32].

4 Data analysis

In section 4.1 and 4.2 the dataset used in analysis, as well as data selection criteria are described. Statistical uncertainties are discussed in section 4.3. Systematic uncertainty estimation as well as correction for weak decays and detector effects are not included in this thesis. Results are presented in section 4.4. They include intensive and strongly intensive quantities for charge multiplicity and net-charge distributions for three different centrality bins.

4.1 Datasets used in analysis

The analysed dataset contains Ar+Sc collisions at beam momentum 75A GeV/c, collected in 2015. Three intervals of centrality were analysed: 0-1%, 0-5%, 0-10%. The whole available statistics, which corresponds to the centrality equal 0-20% was not taken into consideration, due to strong T2 trigger bias. Centrality of the collision was determined with the use of energy deposited by beam spectators in PSD. The procedure of centrality determination was not the subject of this thesis and was performed by Andrey Seryakov for NA61/SHINE Collaboration [33]. In case of Ar+Sc collisions at beam momentum 75A GeV/c, 28 inner PSD modules were chosen (see Fig.14) for centrality selection and for further analysis steps.

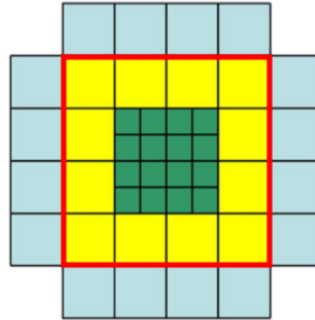


Figure 14: PSD scheme. Chosen 28 modules are surrounded with the red line.

4.2 Data selection criteria

The presented results refer to primary hadrons produced in inelastic Ar+Sc collisions. They are extracted by the application of event and track cuts. The purpose of the event selection is to remove the contamination of off-target and off-time interactions as well as elastic interactions. The aim of the track selection is to reduce the contamination from secondary interactions, weak decays and other sources of non-vertex or bad quality tracks. The cuts used in this analysis were prepared by the NA61/SHINE Collaboration [34].

4.2.1 Event selection

Events, to be accepted, had to meet the following conditions:

4.2 Data selection criteria

- The run number had to be an element of the set of 'valid' runs. The run is accepted as 'valid' if the target during the run was inserted; it was not a test run; the data from the run are properly reconstructed; it does not contain a PSD malfunction; there was neither bad BPD signal nor bad magnetic field and it is stable in time.
- T2 trigger cut - the beam was registered before the target and it was not registered behind the target. It means that the beam interacted with the target. See Tab.1.
- BPD cut - the beam had to be registered in BPD1 or BPD2 detector and necessarily in BPD3 detector.
- BPD charge cut - charge deposited in X plane of BPD3 $\in (3800; 7200)$ and charge deposited in Y plane of BPD3 $\in (3600; 6800)$ [arb. unit]
- WFA cut - the beam particles which are registered by S1 counter in the time window $< \pm 4 \mu s$ around the trigger signal (generated by particle which interacted with the target) were rejected. Also particles which interactions occurred in the time window $< \pm 25 \mu s$ around the T4 signal were rejected.
- Main Ar+Sc Interaction Vertex had to be reconstructed and placed inside the target.
- Energy deposited in 1-16 PSD modules (marked in green in Fig.14) < 1300 GeV and energy deposited in 17-44 PSD modules (marked in yellow and blue in Fig.14) $\in (300, 1700)$ GeV (see Fig.15).

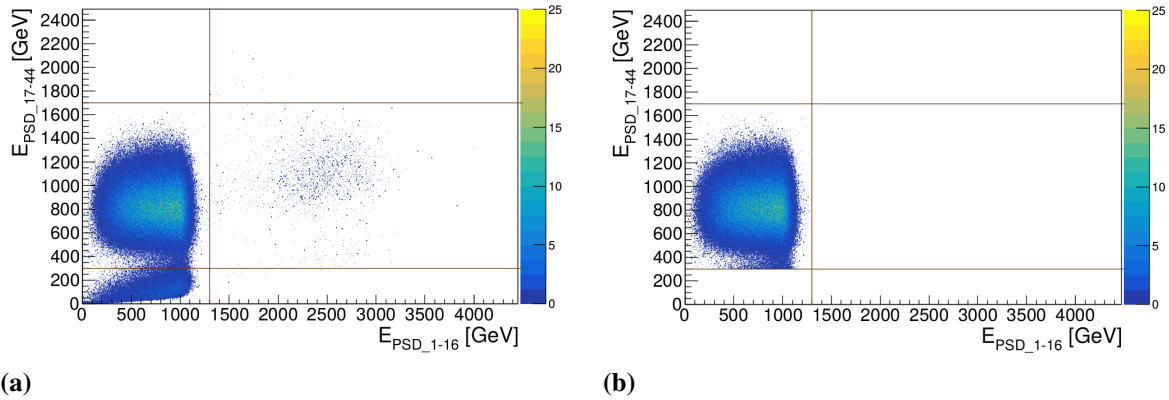


Figure 15: PSD energy in modules 1-16 vs. PSD energy in modules 17-44 distribution before (a) and after (b) the cut.

- Track ratio cut - the ratio of tracks used for vertex fit (VtxTracks) to all registered tracks (allTracks) had to be ≥ 0.17 for number of tracks used for vertex fit < 31 (see Fig.16).
- S5 cut - for ADC value of S5 < 80 , all events which didn't meet the condition $VtxTracks > -(160/2200) * E_{PSD_{allmodules}} + 160$ were removed (see Fig.17).

4.2.2 Track cuts

Particles, to be accepted, had to meet the following conditions:

- Charge of the particle had to be different than zero.
- At least 30 points had to be left by a particle in TPCs.
- At least 15 points had to be left by a particle in Vertex TPCs.
- The distance between the point where extrapolated track fit crosses the interaction plane and the main

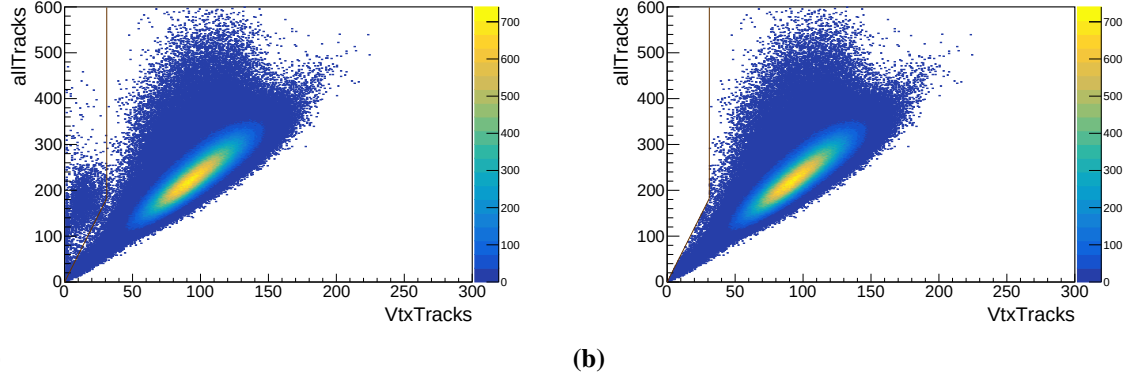


Figure 16: VtxTracks vs. all tracks distribution before (a) and after (b) the cut.

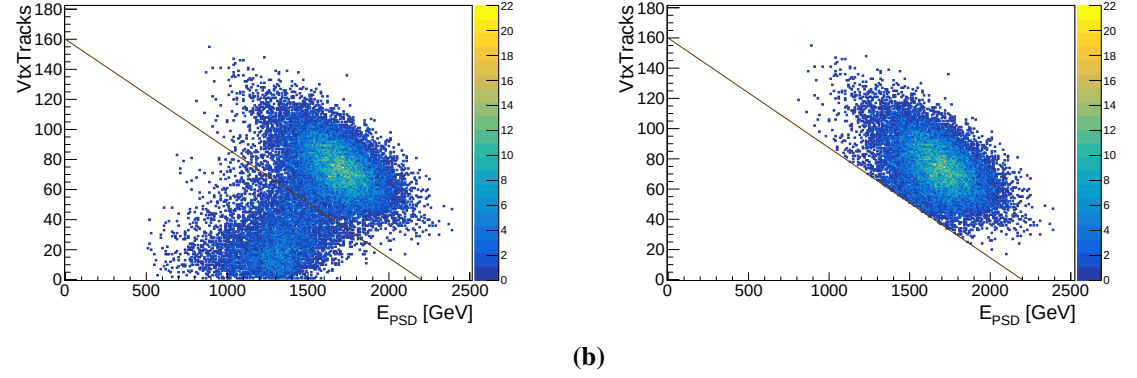


Figure 17: $E_{PSD_{allmodules}}$ vs. VtxTracks distribution before (a) and after (b) the cut.

vertex (track impact parameter) had to meet the conditions: $|B_x| \leq 4$ cm, $|B_y| \leq 2$ cm, to reduce the presence of non-vertex particles (see Fig.18).

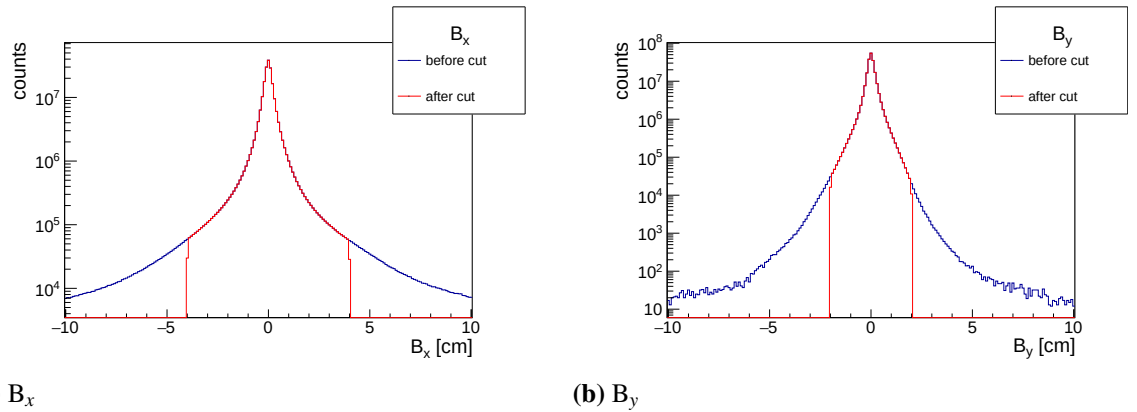


Figure 18: Distributions of track impact parameters in Ar+Sc collision at 75A GeV/c.

- Transverse momentum of a particle (perpendicular to beam direction) had to meet the constraint: $p_T \leq$

4.3 Statistical uncertainties

1.5 GeV/c.

- Particle was neither an electron nor a positron - most of them are created in weak decays.
- Particle had to be within the analysis acceptance (for details see subsection 4.2.3)

4.2.3 Acceptance

In order to compare fluctuations in collisions of different size a common phase-space acceptance region has to be established. Each track has to be inside the acceptance map created for p+p interactions [35] and its rapidity is: $0 \leq y_\pi \leq y_{beam}$. Acceptance map is a three-dimensional table which describes region of reconstruction efficiency of the detector above 90% in p+p collision. It is defined in azimuthal angle, rapidity and transverse momentum calculated in center-of-mass system. It is created with the use of Monte Carlo simulation of p+p interactions. Reconstruction efficiency is defined as the ratio of the number of reconstructed and matched tracks which satisfies the track cuts to the number of all simulated tracks. Additional constraint $y_\pi > 0$ in center-of-mass system was made in order to make the results more comparable between different energies as the backward acceptance ($y_\pi < 0$) changes with collision energy due to large track density for heavier systems. The restriction $y_\pi \leq y_{beam}$ is implemented in order to remove the fragmentation region [36]. Tracks which azimuthal angle, rapidity (calculated assuming pion mass) and transverse momentum not present in the acceptance map are removed. Results of the acceptance cut is presented on Fig.19 and Fig.20.

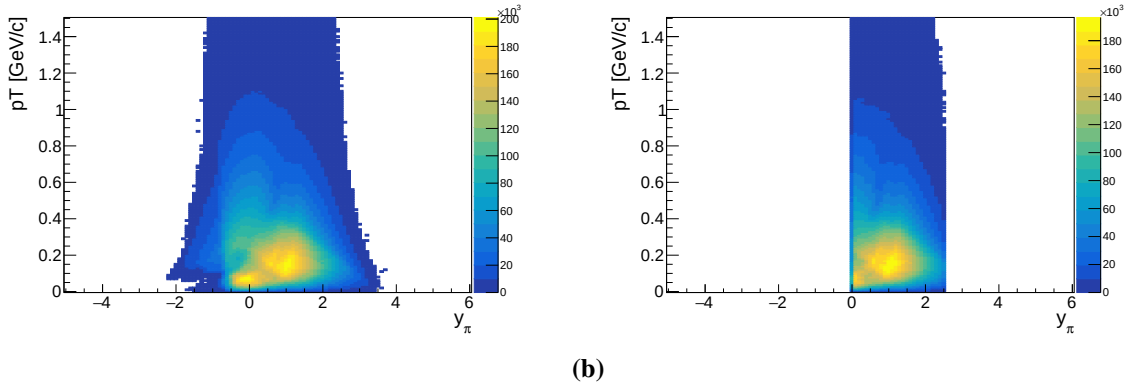


Figure 19: p_T vs. y_π distribution before (a) and after (b) applying acceptance map with additional rapidity cut: $0 \leq y_\pi \leq y_{beam}$.

4.3 Statistical uncertainties

Statistical uncertainties were obtained with the use of bootstrap method [37]. It is one of the methods to estimate statistical uncertainties when low data statistics is available. The bootstrap algorithm which was used is presented below.

To calculate an error of the obtained quantities (scaled variance, scaled skewness, etc.) the following steps have to be done:

1. create the new, empty sample

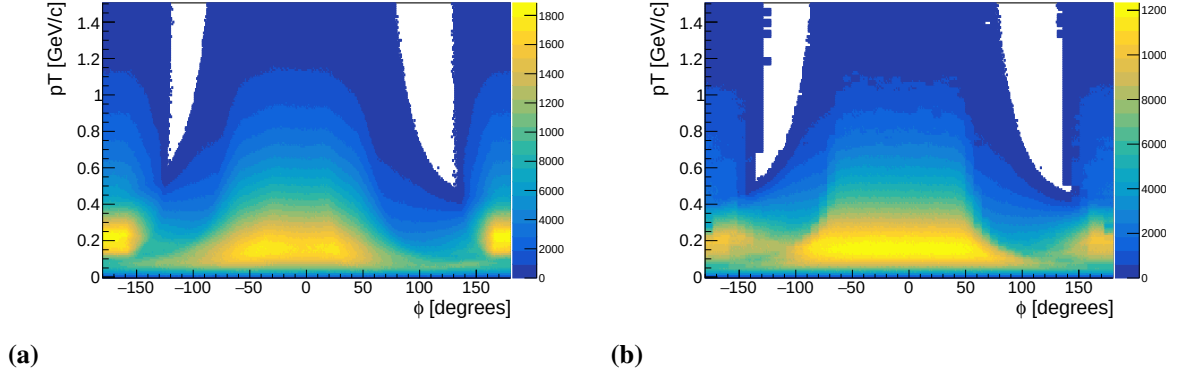


Figure 20: p_T vs. ϕ distribution before (a) and after (b) applying acceptance map with additional rapidity cut: $0 \leq y_\pi \leq y_{beam}$.

2. fill the new sample using sampling with replacement: take any value of multiplicity (and E_P - see Eq.18) from the original sample and put it into the new sample and repeat it until the new sample have the same size as the original sample
3. perform the analysis on the new sample as was performed on the original sample, i.e. calculate intensive or strongly intensive quantities
4. store obtained results
5. repeat all above steps to get sufficient statistics - in this research the procedure was repeated 500 times

Sample histogram which was created with the use of bootstrap method is shown in Fig.21. The obtained distribution should be close to Gauss distribution. Then the statistical uncertainty can be estimated as the standard deviation of the histogram. The resolution of the bootstrap method depends

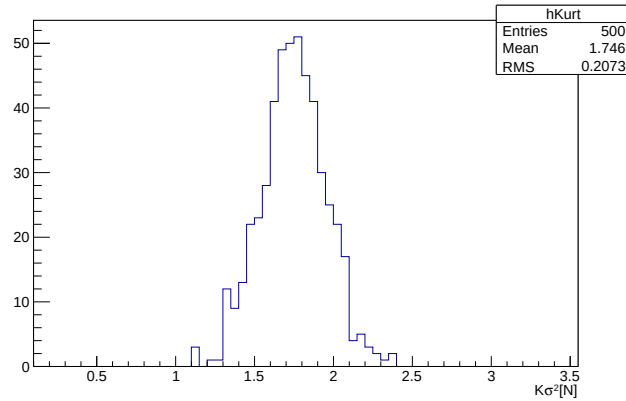


Figure 21: Histogram of scaled kurtosis of net-charge distribution from Ar+Sc collision at 75A GeV/c, centrality 0-10%, from 500 bootstrap samples.

on the number of newly created samples. Such dependence was investigated for scaled variance, scaled

4.4 Results

skewness and scaled kurtosis from a single wounded nucleon of all charged particles distribution at centrality 0-10%. The results are shown in Fig.22.

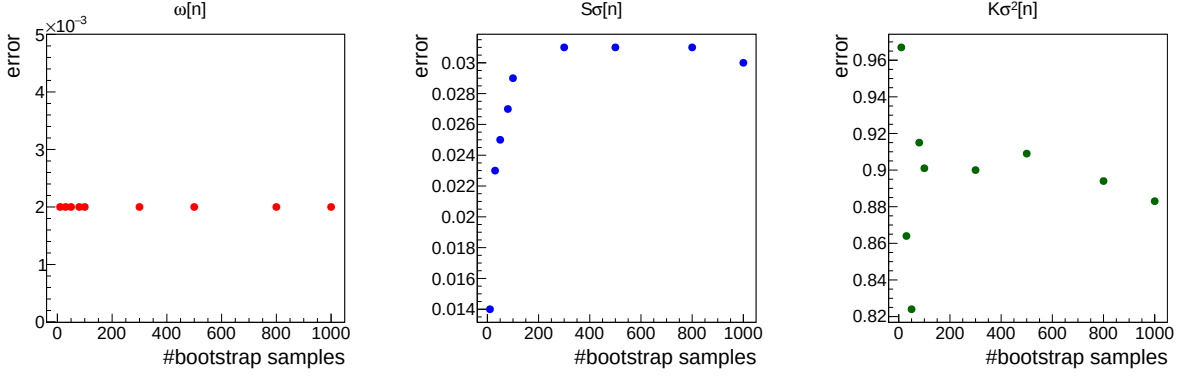


Figure 22: Stability of bootstrap method for quantities from a single wounded nucleon: scaled variance $\omega[n]$, scaled skewness $S\sigma[n]$ and scaled kurtosis $K\sigma^2[n]$ of all-charge distribution in Ar+Sc collision, centrality 0-10%

Statistical uncertainties calculated with the use of bootstrap method were compared to errors calculated with use of subsamples method used by NA49 and in previous analysis of NA61/SHINE. In the subsamples method the data were divided for 30 subsamples and the statistical uncertainty was taken as the dispersion of the sub-sample distribution divided by $\sqrt{30}$. The comparison was made for statistical errors of strongly intensive quantities calculated for all-charged distribution at centrality 0-10%. The results are presented in Tab.2.

	bootstrap	subsamples
$\omega[n]$	0,002	0,002
$S\sigma[n]$	0,031	0,023
$K\sigma^2[n]$	0,909	0,726

Table 2: Error of strongly intensive quantities obtained using bootstrap method and subsamples method for 0-10% most central Ar+Sc collisions at 75A GeV/c.

The statistical error of scaled variance is the same for both methods. The statistical error of skewness and kurtosis is larger if calculated using bootstrap than if calculated using subsamples method. For higher order moments the bootstrap method seems to be a better approach as they strongly depend on available statistics (especially fourth moment).

4.4 Results

The analysis of intensive and strongly intensive quantities of multiplicity distributions (positively (N+), negatively (N-) and all (Nch) charged particles) and net-charge distribution was performed for three intervals of centrality: 0-1%, 0-5%, 0-10%. Analysed distributions are presented in Fig.23.

It can be observed that the mean value of all distributions (with exception of net-charge) decreases with increasing centrality interval. It is an expected behaviour. Smaller centrality interval means that the

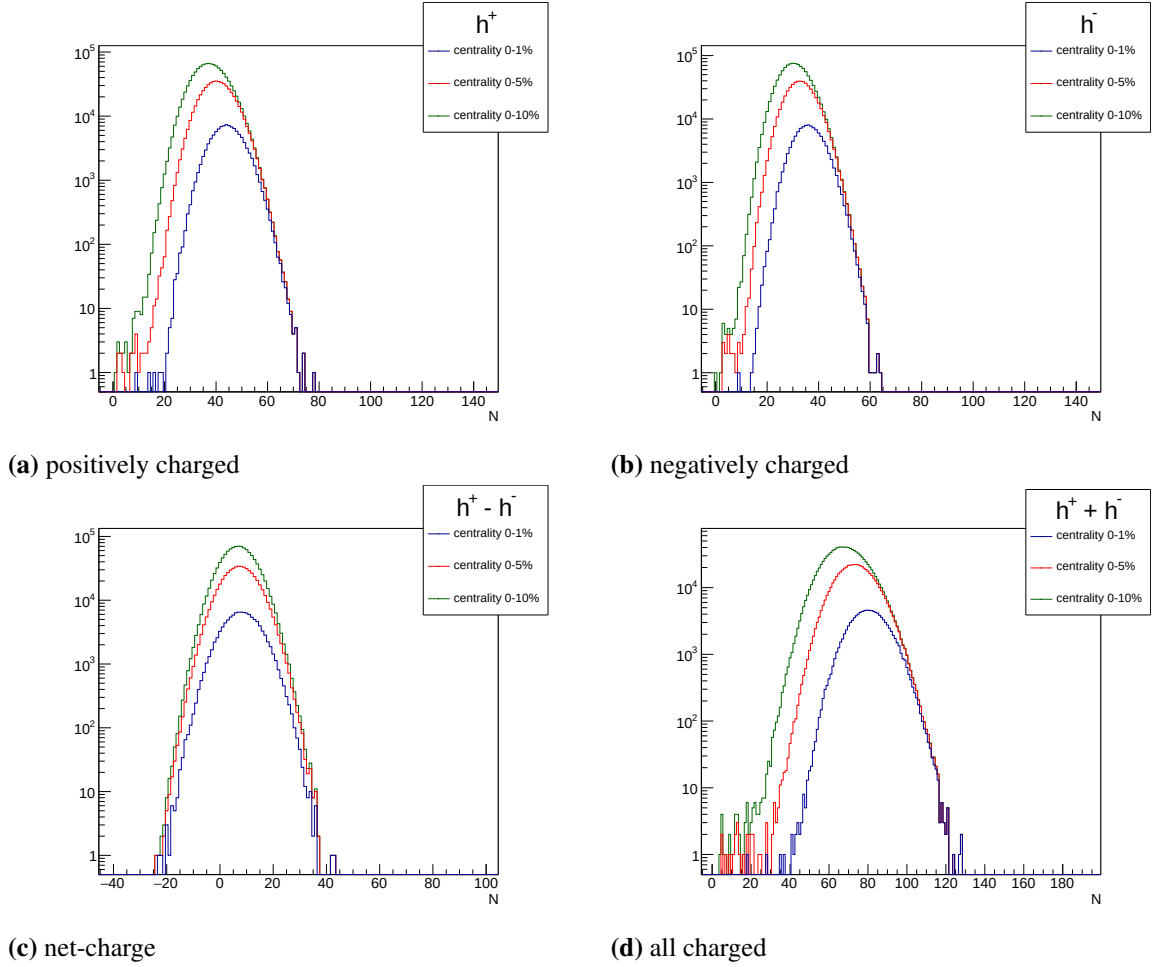


Figure 23: Multiplicity and net-charge distributions for centrality intervals: 0-1%, 0-5%, 0-10%.

collisions are more central, so one can expect that the average number of produced particles in each event is larger than for more peripheral collisions.

4.4.1 Intensive quantities

The obtained intensive quantities of multiplicity and net-charge distributions, calculated with the use of Eq.5,6,7, are presented in Tab. 3.

The following behaviour is observed:

- Scaled variance of all distributions increases with the width of centrality bin. For the most central collisions $\omega[N]$ of N^+ and N^- is < 1 , then it increases to values > 1 for wider centrality bin. $\omega[N]$ of N_{ch} is > 1 for all centralities. $\omega[N]$ of net-charge is $\gg 1$. This is an expected behaviour as reference distribution for net-charge distribution is not Poisson, but Skellam distribution.
- Scaled skewness increases with the width of centrality bin. For the most central collisions $S\sigma[N]$ of N^+ and N^- is < 1 , then it increases to values > 1 . $S\sigma[N]$ of N_{ch} is > 1 for all centralities.
- Scaled kurtosis shows non-monotonic behaviour with increasing the width of centrality bin.

4.4 Results

centrality	quantity	N+		N-		net		Nch	
		val	err	val	err	val	err	val	err
1	$\omega[N]$	0,870	0,004	0,864	0,004	5,699	0,280	1,157	0,005
	$S\sigma[N]$	0,706	0,048	0,793	0,041	0,171	0,049	1,093	0,750
	$K\sigma^2[N]$	2,377	0,695	1,621	0,513	1,255	0,708	5,891	1,978
5	$\omega[N]$	0,990	0,002	0,964	0,002	5,748	0,013	1,374	0,003
	$S\sigma[N]$	0,924	0,022	0,948	0,019	0,198	0,216	1,405	0,038
	$K\sigma^2[N]$	2,609	0,371	2,352	0,264	1,211	0,300	11,132	1,187
10	$\omega[N]$	1,191	0,002	1,123	0,002	5,808	0,009	1,733	0,002
	$S\sigma[N]$	1,225	0,016	1,219	0,014	0,313	0,015	1,913	0,026
	$K\sigma^2[N]$	1,901	0,251	2,079	0,193	1,759	0,206	6,051	0,719

Table 3: Intensive measures: scaled variance ($\omega[N]$), scaled skewness ($S\sigma[N]$), scaled kurtosis ($K\sigma^2[N]$) for different set of particles and different centralities in Ar+Sc at 75A GeV/c.

4.4.2 Strongly intensive quantities

In order to compare current analysis with those already performed for Ar+Sc at 75A GeV/c, $\Omega[N, E_P]$ quantity was calculated for multiplicity distributions for centrality 0 – 1% and 0 – 5%. Symbol N in the formula denotes the multiplicity and E_P is the forward energy of participants, obtained as:

$$E_P = E_{beam} - E_{spectators} \quad (18)$$

where E_{beam} is the energy of the beam and $E_{spectators}$ is the energy of the projectile spectators measured in previously chosen 28 inner modules of PSD. The aim of these calculations was the comparison with the preliminary NA61/SHINE results [27] to confirm that the method of the analysis is correct. Obtained results and the comparison is presented in Tab.4.

		N+		N-		Nch	
centrality		val	err	val	err	val	err
0-1%	preliminary	0,834	0,004	0,823	0,003	1,065	0,005
	current	0,820	0,004	0,824	0,003	1,067	0,004
0-5%	preliminary	0,859	0,002	0,843	0,002	1,108	0,002
	current	0,847	0,002	0,848	0,002	1,114	0,002

Table 4: $\Omega[N, E_P]$ calculated for multiplicity distributions of Ar+Sc collisions at 75A GeV/c.

The results are not identical, nevertheless the agreement is satisfactory. The probable source of disagreement between results is different production of data used for analysis and slight difference in acceptance cut definition.

Strongly intensive quantities of multiplicity and net-charge distributions were also calculated with the use of Eq.15,16,17, where N is multiplicity or net-charge in a given event and B is forward energy of participants. Obtained results are presented in Tab.5.

centrality	quantity	N+		N-		net		Nch	
		val	err	val	err	val	err	val	err
1	$\omega[n]$	0,820	0,004	0,824	0,003	5,687	0,028	1,067	0,004
	$S\sigma[n]$	0,477	0,050	0,657	0,042	0,139	0,047	0,651	0,078
	$K\sigma^2[n]$	1,208	0,786	1,198	0,534	1,053	0,743	3,292	2,189
5	$\omega[n]$	0,847	0,003	0,848	0,002	5,722	0,007	1,115	0,004
	$S\sigma[n]$	0,360	0,025	0,542	0,012	0,121	0,012	0,221	0,048
	$K\sigma^2[n]$	0,828	0,369	1,203	0,273	0,740	0,175	7,341	1,125
10	$\omega[n]$	0,895	0,001	0,882	0,001	7,752	0,009	1,196	0,002
	$S\sigma[n]$	0,207	0,018	0,456	0,015	0,151	0,015	-0,188	0,031
	$K\sigma^2[n]$	0,106	0,256	0,460	0,197	0,760	0,206	4,258	0,859

Table 5: Strongly intensive measures: scaled variance ($\omega[n]$), scaled skewness ($S\sigma[n]$), scaled kurtosis ($K\sigma^2[n]$) from a single wounded nucleon for different set of particles and different centralities in Ar+Sc at 75A GeV/c.

The following behaviour is observed:

- Scaled variance from a single wounded nucleon behaviour is qualitatively the same as behaviour of intensive scaled variance.
- Scaled skewness from a single wounded nucleon decreases (with exception of net-charge) with the width of centrality bin. This is the opposite behaviour comparing to the intensive scaled skewness.
- Scaled kurtosis from a single wounded nucleon behaviour is qualitatively the same as behaviour of intensive scaled kurtosis.

4.4.3 Centrality dependence of intensive and strongly intensive quantities

In Wounded Nucleon Model or Grand Canonical Ensemble in Boltzmann limit, intensive quantities are independent on the system size, but dependent on fluctuations of the system size. The dependence on fluctuations on the system size can be removed by using strongly intensive quantities. In heavy ion collisions, the larger centrality interval is taken into consideration, the larger are fluctuations of the system size. Thus, it is expected that strongly intensive quantities are independent on increasing centrality interval while intensive quantities depend on it. Comparison of both types of quantities are presented in Figs.24, 25, 26. The error bars are usually smaller than the marker size.

The following behaviour was observed:

- Scaled variance from a single wounded nucleon depends slightly on centrality selection, unlike the intensive scaled variance, which depends strongly on it (with exception of net-charge).
- Scaled skewness from a single wounded nucleon decreases with increase of the centrality bin width (with exception of net-charge). This behaviour is opposite to intensive scaled skewness which increases with the increase of system size.
- Scaled kurtosis from a single wounded nucleon depends slightly on centrality bin width (with exception of Nch).

Comparison with p+p interactions at 80 GeV/c:

- Scaled variance from a single wounded nucleon of net-charge is bigger than the corresponding value

4.4 Results

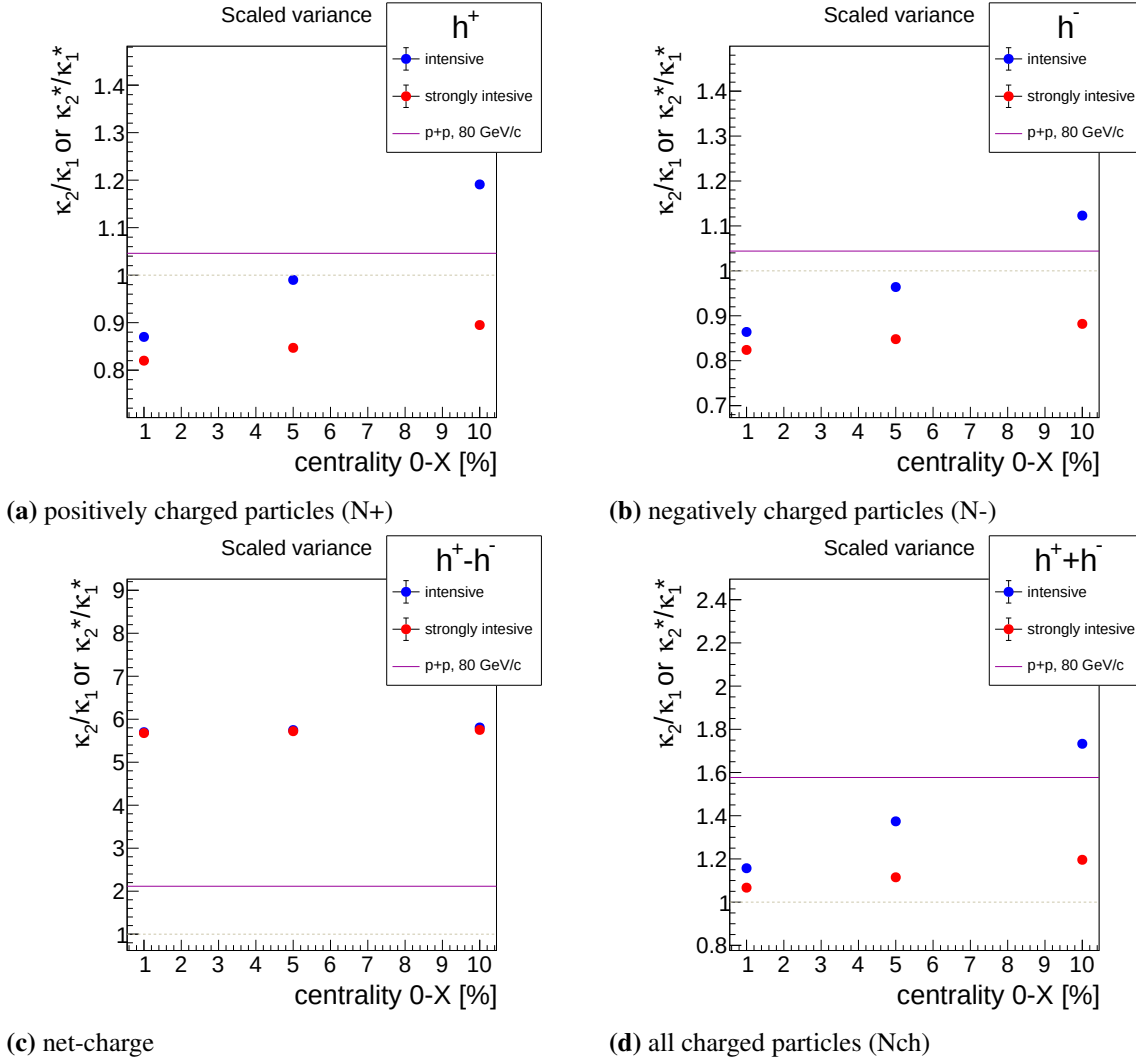


Figure 24: Centrality dependence of scaled variance ($\omega[N]$) - blue points and scaled variance from a single wounded nucleon ($\omega[n]$) - red points in Ar+Sc collisions at 75A GeV/c. Purple line is the preliminary result for p+p collision at 80 GeV/c beam momentum [38].

for p+p collision, scaled variance from a single wounded nucleon of N+, N- and Nch is smaller than the corresponding value for p+p collision.

- Scaled skewness from a single wounded nucleon of N- and net-charge is smaller than the corresponding value for p+p collision.
- Scaled kurtosis from a single wounded nucleon of N- and net-charge is approximately equal to the corresponding value for p+p collision.

These are the first results of higher moments from ion+ion collision in NA61/SHINE experiment. Non-monotonic changes are seen in strongly intensive kurtosis when compare Ar+Sc to p+p results. The further analysis of the rest of the systems as well as the systematic uncertainties is necessary to determine the origin of this effect.

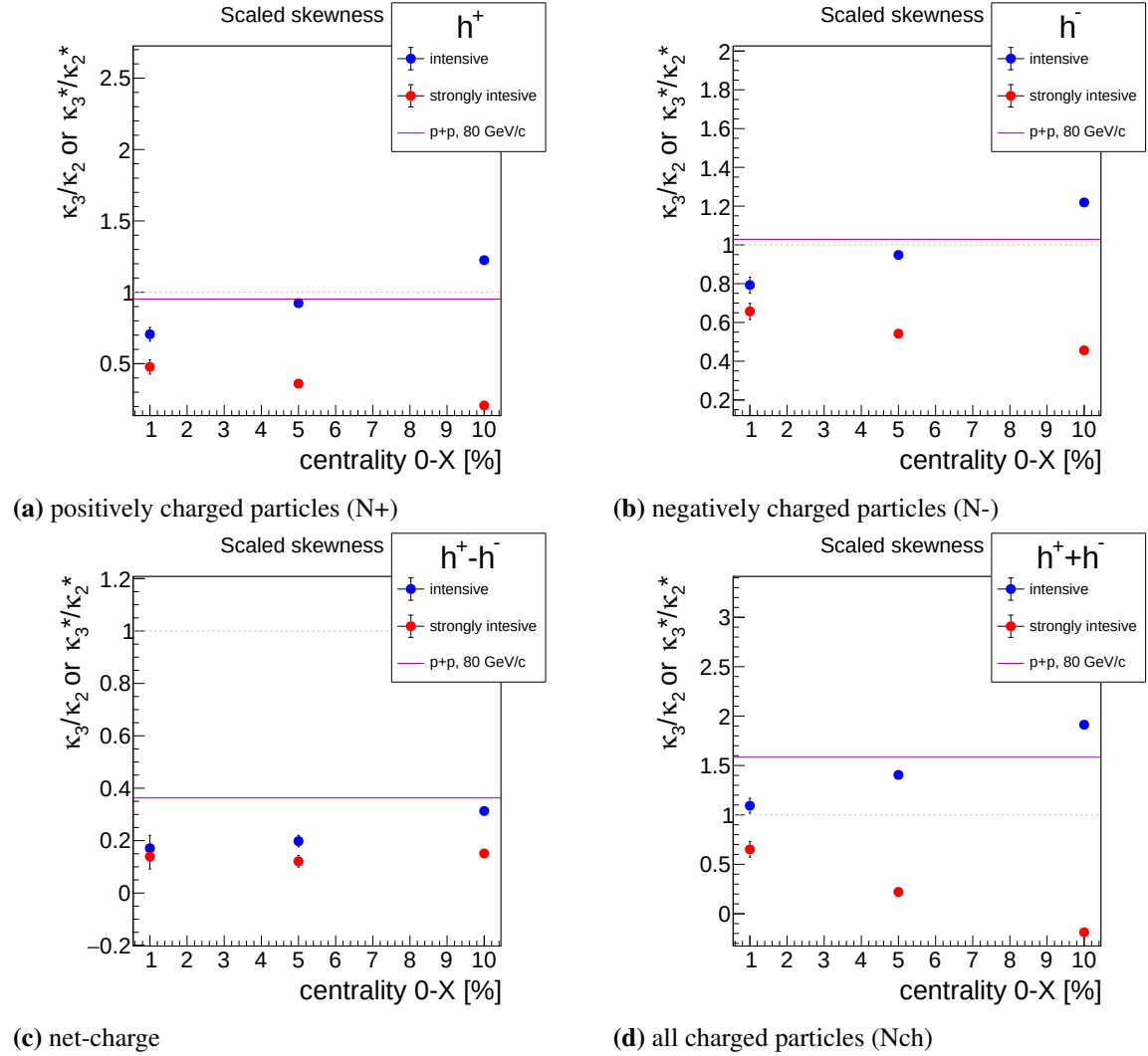


Figure 25: Centrality dependence of scaled skewness ($S\sigma[N]$) - blue points and scaled skewness from a single wounded nucleon ($S\sigma[n]$) - red points in Ar+Sc collisions at 75A GeV/c. Purple line is the preliminary result for p+p collision at 80 GeV/c beam momentum [38].

5 Conclusions

This work is an important part of NA61/SHINE physics programme which performs system-size and energy scan of phase diagram of strongly interacting matter in order to search for critical point. The higher order moments of multiplicity and net-charge distributions for Ar+Sc collisions at 75A GeV/c were analysed for the first time and the results were presented in this thesis.

$\Omega[N, E_P]$ quantity was calculated and compared to the preliminary NA61/SHINE results. Satisfactory compliance was obtained what confirmed the correctness of the analysis method.

Moments of multiplicity and net-charge distributions up to fourth were analysed with use of intensive

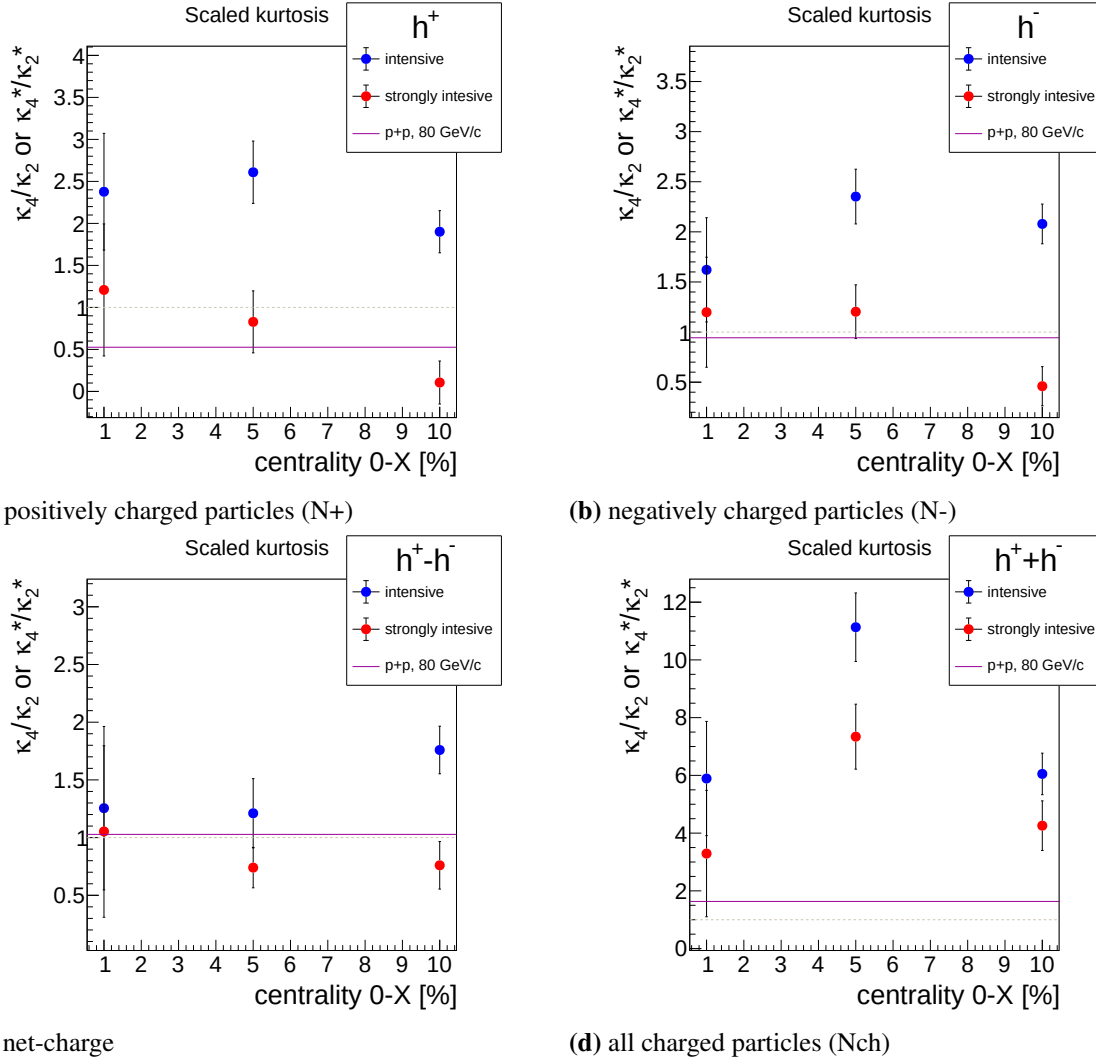


Figure 26: Centrality dependence of scaled kurtosis ($K\sigma^2[N]$) - blue points and scaled kurtosis from a single wounded nucleon ($K\sigma^2[n]$) - red points in Ar+Sc collisions at 75A GeV/c. Purple line is the preliminary result for p+p collision at 80 GeV/c beam momentum [38].

and strongly intensive quantities. The analysis was performed for three centrality bins: 0 – 1%, 0 – 5%, 0 – 10%. Both intensive and strongly intensive quantities shows centrality dependence, although the dependence is much stronger in case of intensive quantities, what is an expected result. The strongly intensive quantities were compared to the preliminary NA61/SHINE results of p+p interactions at 80 GeV/c. The greatest change in behaviour between different centrality bin widths is observed in scaled kurtosis. Further investigation of other energies and systems as well as systematical uncertainties is needed to find the origin of the visible effect.

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