



Multiplicity and net-electric charge fluctuations in central Ar+Sc interactions at 13A, 19A, 30A, 40A, 75A, and 150A GeV/c beam momenta measured by NA61/SHINE at the CERN SPS

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Abstract This paper presents results on multiplicity fluctuations of positively and negatively charged hadrons as well as net-electric charge fluctuations measured in central Ar+Sc interactions at beam momenta 13A, 19A, 30A, 40A, 75A, and 150A GeV/c. The fluctuation analysis is one of the tools to search for the predicted critical point of strongly interacting matter. Results are corrected for the experimental biases and quantified using cumulant ratios. In most instances, multiplicity and net-charge distributions appear narrower than the corresponding Poisson or Skellam distributions. Cumulant ratios are compared with the EPOS1.99 model predictions, which provide a qualitative description that aligns with observations for positively and negatively charged particles. The obtained results are also compared to earlier NA61/SHINE results from inelastic $p+p$ interactions in the same analysis acceptance.

1 Introduction

This paper presents measurements of the multiplicity and net-electric charge event-by-event fluctuations in central $^{40}\text{Ar}+^{45}\text{Sc}$ collisions at beam momenta (p_{beam}) of 13A, 19A, 30A, 40A, 75A, and 150A GeV/c by NA61/SHINE at the CERN Super Proton Synchrotron (SPS). The corresponding energy per nucleon pair in the center-of-mass system is $\sqrt{s_{\text{NN}}} = 5.1, 6.1, 7.6, 8.8, 11.9, \text{ and } 16.8 \text{ GeV}$. This study is a part of the NA61/SHINE strong interaction program [1, 2] and is devoted to the search for the critical point of strongly interacting matter [3]. The study of the phase diagram of strongly interacting matter is the main aim of the two-dimensional scan of the collision energy and the colliding system size performed by the NA61/SHINE experiment.

The measurement of fluctuations in nucleus-nucleus (A+A) collisions is one of the most promising tools for searching for the critical point (CP) as fluctuations are sensi-

tive to the change of the correlation length in the system [4, 5]. The fluctuations are also sensitive to the size of the system and varying collision geometry. Appropriate statistical methods and careful data selection are employed to mitigate the impact of these unwanted effects on the presented results. In this paper, so-called intensive fluctuation measures are utilized for the comparison between different system sizes. Also, only central Ar+Sc collisions were selected for the analysis to reduce varying collision geometry. The presented intensive quantities were already successfully used; for details, see Refs. [6–8].

The paper is organized as follows. In Sect. 2, intensive measures of fluctuations are briefly introduced. The experimental setup of NA61/SHINE is presented in Sect. 3. Data processing and analysis procedures are described in Sect. 4. The results and their comparison with model calculations and $p+p$ results are discussed in Sect. 5. Section 6 contains the summary of this study.

The following variables and definitions are used in this paper. The particle rapidity y is calculated assuming pion mass in the collision center-of-mass system (cms), $y = 0.5 \ln[(E + p_L)/(E - p_L)]$, where E and p_L are the particle energy and longitudinal momentum, respectively. The transverse component of the momentum is denoted as p_T , the electric charge as q , and the azimuthal angle as ϕ . It is defined as the angle between the transverse momentum vector and the horizontal (x) axis. The collision energy per nucleon pair in the center-of-mass system is denoted as $\sqrt{s_{\text{NN}}}$.

2 Measures of multiplicity and net-charge fluctuations

The shape of the multiplicity and net-electric charge (for simplicity called further net-charge) distributions can provide information about the structure of the strongly interacting matter phase diagram [4]. It is quantified by moments, cumulants, and a combination of these quantities [9]. The

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multiplicity and net-charge fluctuations may be sensitive to the presence of CP, and this sensitivity increases with the order of measured quantities [9, 10].

Intensive quantities are the quantities independent of the volume of the system (V) within the ideal Boltzmann gas model described by the Grand Canonical Ensemble (IB-GCE) [11], or of the number of wounded nucleons (W) within the Wounded Nucleon Model [12]. Intensive quantities can be calculated by dividing two extensive quantities, which are proportional to the size of the system. Extensive quantities are, for example, cumulants (κ_i , where i is the order of the cumulant) or the algebraic or central moments of the distribution. For instance, the mean multiplicity of produced charged hadrons $\langle N \rangle$ is κ_1 and the variance of the distribution $\sigma^2 = \langle N^2 \rangle - \langle N \rangle^2$ is κ_2 . The third-order cumulant, κ_3 , is equal to the third central moment $\mu_3 = \langle (N - \langle N \rangle)^3 \rangle$ and κ_4 is given by $\mu_4 - 3\sigma^4$, where $\mu_4 = \langle (N - \langle N \rangle)^4 \rangle$.

The intensive quantities studied in this paper are scaled variance, scaled skewness, and scaled kurtosis. If there are no fluctuations, the value of intensive quantities is equal to zero [13]. If the multiplicity varies according to the Poisson distribution, the value of intensive quantities equals unity. In IB-GCE, the net-charge, defined as a difference of positive and negative charges, is given by the Skellam distribution (not Poisson). For this reason, the intensive quantities of the net-charge distribution are slightly modified to keep zero and unity as reference values. As a result, the final quantities considered in this paper are obtained as cumulant ratios in the following way:

- (i) for multiplicity distributions:

$$\frac{\kappa_2}{\kappa_1}, \quad \frac{\kappa_3}{\kappa_2}, \quad \text{and} \quad \frac{\kappa_4}{\kappa_2}. \quad (1)$$

- (ii) for net-charge:

$$\frac{\kappa_2}{\kappa_1^+ + \kappa_1^-}, \quad \frac{\kappa_3}{\kappa_1}, \quad \text{and} \quad \frac{\kappa_4}{\kappa_2}, \quad (2)$$

where κ_1^+ and κ_1^- are the first cumulants of multiplicity distribution for particles of the corresponding charge.

In nucleus-nucleus collisions, it is experimentally challenging to determine the volume of the created system precisely. Collisions of similar volume are grouped in so-called centrality classes, from peripheral to central ones. The influence of the volume fluctuations on the intensive quantities for systems of different sizes is discussed in Ref. [14]. Volume fluctuations are addressed by selecting the most central collisions where the fluctuations are relatively small. Moreover, it is a known fact that the kinematic acceptance of the detector may affect measured ratios [9]. Thus, a well-defined

phase-space region in rapidity, transverse momentum, and azimuthal angle is also provided. For details, see Sect. 4.

3 NA61/SHINE detector

The NA61/SHINE detector, depicted in Fig. 1, is a large-acceptance hadron spectrometer situated in CERN North Area. Beam delivery to the detector occurs via the H2 beam-line from the Super Proton Synchrotron (SPS) [2]. Three Beam Position Detectors (BPDs) and a set of scintillator counters (S1, S2, V1) are utilized upstream of the spectrometer to measure beam position and time references.

The detection system consists of four Time Projection Chambers (TPCs) responsible for tracking charged particles produced in collisions. Positioned downstream of the target and along the beamline are two Vertex TPCs (VTPCs) enclosed within superconducting magnets with a combined bending power of up to 9 Tm. The magnetic field is scaled proportionally to the beam momentum to maintain momentum acceptance similar for different collision energies. Placed symmetrically on both sides of the beamline, downstream of the VTPCs, are the Main TPCs (MTPCs) and two walls of pixel Time-of-Flight (ToF-L/R) detectors. The VTPCs are filled with an Ar:CO₂ gas mixture in the ratio 90:10, while the MTPCs utilize a mixture of 95:5.

Downstream of the MTPCs, the Projectile Spectator Detector (PSD) is located. It is a high-resolution calorimeter centered on the beam. It measures the energy flow around the beam direction allowing for selecting the desired collision centrality.

3.1 Target

For the collisions of $^{40}\text{Ar}+^{45}\text{Sc}$ nuclei, the experiment utilized targets obtained from Stanford Advanced Materials. The targets were 2×2 cm plates with thicknesses of 2 mm and 4 mm, comprising more than 99% of Sc [15]. Both plates were used during the data collection. The target was positioned at $z \approx -580$ cm (upstream of the VTPC-1 front wall) within a special target holder [2]. This target holder maintained a helium atmosphere around the target, reducing the likelihood of off-target interactions that would result from the beam interacting with the air in the vicinity of the target.

3.2 Beam and triggers

The ^{40}Ar beam delivered by the SPS accelerator was the primary beam explicitly designed for NA61/SHINE. The experiment successfully conducted collisions using beams at six different momenta: 13A, 19A, 30A, 40A, 75A, and 150A GeV/c with the scandium targets.

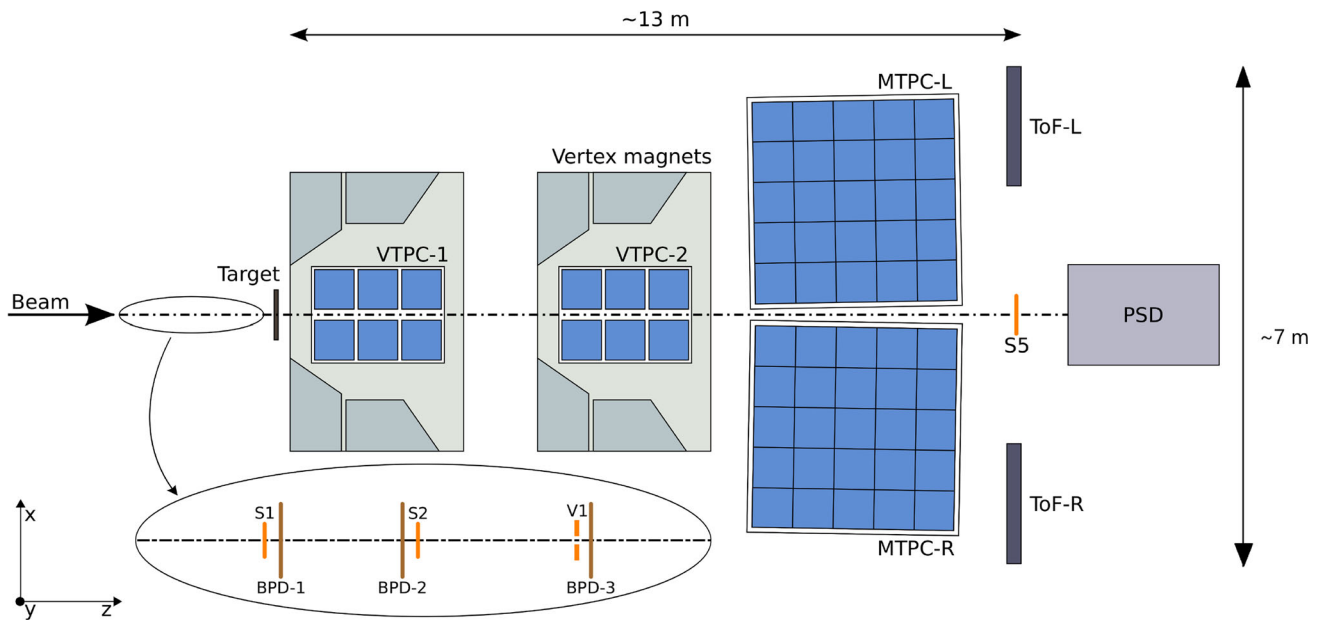


Fig. 1 The schematic layout of the NA61/SHINE [2] detector as used for the $^{40}\text{Ar}+^{45}\text{Sc}$ energy scan (horizontal cut, not to scale). The inset provides a closer view of the beam and trigger detector configuration. The plot illustrates the alignment of the NA61/SHINE coordinate sys-

tem, with its origin located in the middle of VTPC-2 along the beam axis. The z axis represents the beam direction, while the magnetic field is designed to bend charged particle trajectories in the x - z (horizontal) plane. The drift direction in the TPCs aligns with the y (vertical) axis

Two scintillation counters, S1 and S2, are responsible for defining the beam, along with a veto counter, V1, featuring a 1 cm diameter hole, defining the beam position before reaching the target. Counter S1 also serves as the timing reference (start time) for all counters. The trigger signal to detect beam particles requires a coincidence of these three signals:

$$T1 = S1 \wedge S2 \wedge \overline{V1}. \quad (3)$$

The T4 trigger is based on the breakup of the beam ion due to interactions both in and downstream of the target. It indicates a minimum bias interaction within the target, necessitating an incoming beam particle signal (T1) and a signal lower than that of beam nuclei from the S5 counter. The S5 counter, a scintillator with a diameter of 2 cm, is positioned on the beam downstream of the MTPCs. The T4 trigger condition is denoted as:

$$T4 = T1 \wedge \overline{S5}. \quad (4)$$

Additionally, a threshold is set in sixteen central PSD modules to select approximately 20–30% of the most central collisions (this value varies with different beam momenta). These modules mainly measure the energy of the projectile spectators, so a signal below the set threshold indicates central interaction. The trigger logic for events meeting these criteria is:

$$T2 = T4 \wedge \overline{\text{PSD}}. \quad (5)$$

The presented results are obtained using the events collected with the T2 trigger.

4 Analysis

The objective of the analysis was to measure the fluctuations in multiplicity and net-charge of charged hadrons produced in strong interactions and electromagnetic decays in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ collisions within the selected acceptance. The acceptance is defined by the $y - p_T - \phi$ region, representing the high-efficiency area of the detector in the case of Ar+Sc interactions [16]. The analysis procedure involved the following steps:

- (i) data selection based on the event and track selection criteria to ensure the highest data quality,
- (ii) evaluation of the distributions of charged hadron multiplicities and net-charge,
- (iii) correction of the charged hadron multiplicity and net-charge distributions using the unfolding method,
- (iv) calculation of the fluctuation measures from the corrected distributions,
- (v) estimation of the statistical and systematic uncertainties of the results.

Table 1 Numbers of accepted events that passed the event selection criteria

p_{beam} (GeV/c)	$\sqrt{s_{\text{NN}}}$ (GeV)	1% most central events
13A	5.1	49435
19A	6.1	52408
30A	7.6	91019
40A	8.8	129751
75A	11.9	116103
150A	16.8	46452

4.1 Data processing

4.1.1 Event selection

The analysis involved several selection criteria to ensure the quality and reliability of the data. These criteria are as follows:

- (i) The initial event preselection was carried out using the hardware central interaction trigger T2, specifically configured to use signals from the sixteen small PSD modules (see Sect. 4.1.3). T2 accepted a fraction of the most central interactions, characterized by the lowest forward energy deposited in these modules. The fraction depends on the specific beam momentum.
- (ii) Within the analysis, events with any off-time beam particles within a time window of $\pm 4 \mu\text{s}$ around the trigger particle were excluded. Furthermore, events with any interaction detected within a time window of $\pm 25 \mu\text{s}$ around the trigger particle were also eliminated.
- (iii) For an accurate measurement of the beam particle trajectory, it was essential to have simultaneous signals in either BPD-1 or BPD-2, along with the signal in BPD-3.
- (iv) The main vertex z -coordinate of the event has to be between $\pm 8 \text{ cm}$ around the center of the Sc target (see Fig. 2),
- (v) An upper cut on the energy E_{PSD} measured in the PSD in order to select the 1% most central collisions was introduced. For the detailed centrality selection procedure, see Sect. 4.1.3.

The number of events remaining for the analysis is listed in Table 1.

4.1.2 Track selection

To focus on the primary charged hadron distributions and minimize contamination from secondary and off-time interactions, as well as weak decays, the following track selection criteria were implemented:

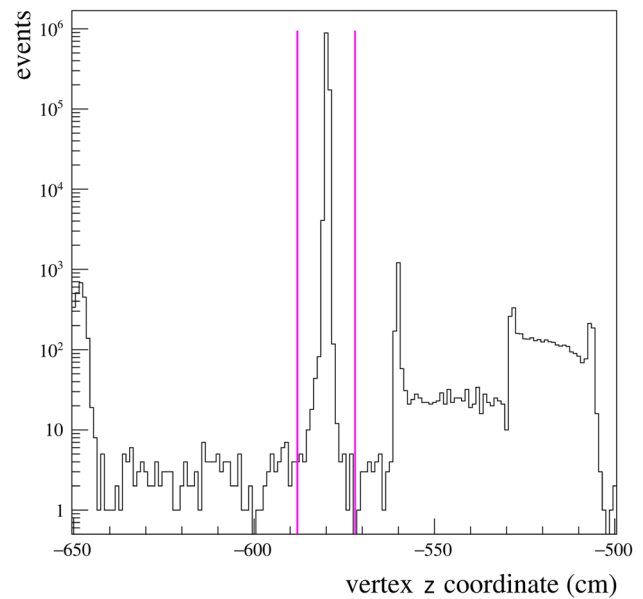


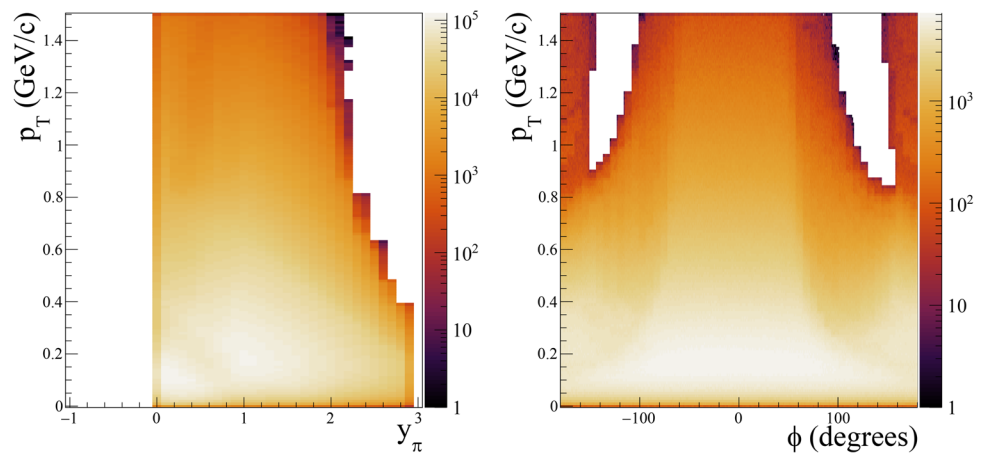
Fig. 2 Distribution of the z coordinate of the fitted primary vertex for the T2-triggered events of $^{40}\text{Ar}+^{45}\text{Sc}$ interactions at 150A GeV/c. The vertical lines indicate the z region selected for the analysis. The z position of the center of the target is equal to -580 cm

- (i) the track momentum fit at the primary vertex should have converged,
- (ii) the total number of reconstructed points on the TPC track should be greater than 30,
- (iii) the sum of the number of reconstructed points in VTPC-1 and VTPC-2 should be greater than 15,
- (iv) the distance between the track extrapolated to the interaction plane and the vertex (track impact parameter) is required to be smaller than 4 cm in the horizontal (bending) plane and 2 cm in the vertical (drift) plane,
- (v) the mean ionization energy loss measured for a given track does not indicate an electron or positron candidate,
- (vi) a track remains in the high-efficiency region of the detector [16], see Fig. 3.

4.1.3 Selection of central collisions

This section presents the selection procedure of the 1% most central events using the PSD calorimeter. The final results presented in this paper refer to the 1% of Ar+Sc collisions with the lowest value of the forward energy E_F (most central collisions). The quantity E_F represents the total energy deposit of all particles produced in the $^{40}\text{Ar}+^{45}\text{Sc}$ collision via strong and electromagnetic processes within the forward rapidity region defined by the PSD acceptance map [17], as well as nuclear fragments emitted in this region. While E_F can be obtained from models, it is not directly available in the experimental data.

Fig. 3 Distribution of charged particle tracks in the acceptance region selected for the analysis in the $y - p_T - \phi$ space, for $^{40}\text{Ar}+^{45}\text{Sc}$ interactions at 150A GeV/c. The rapidity y_π of each particle is calculated assuming pion mass



Instead, the NA61/SHINE experiment measures E_{PSD} in PSD which corresponds to E_F . A specific subset of PSD modules is used for its calculation to ensure the closest possible approximation of E_{PSD} to E_F . The precise value of E_{PSD} , its correspondence to E_F and the percentage of selected centrality were based on performed tests [14,18]. Figure 4 shows which modules were used to obtain E_{PSD} at a given beam momentum. The selection of these modules is optimized for each beam momentum by analyzing the correlation between the mean module energy and the total multiplicity of charged particles registered in the TPCs. The E_{PSD} calculation is performed on the data preselected by the hardware central interaction trigger T2. The distributions of E_{PSD} are shown in Fig. 5. For details on T2 selection and comparison to minimum bias events, see Ref. [19].

In Monte Carlo simulations, centrality was selected directly using either E_F or the simulated value of E_{PSD} . The simulated E_{PSD} represents energy stored in the simulated PSD. The simulation accounts for various PSD effects on energy measurements, including energy leakage, energy smearing, and measurement resolution. Its purpose is to replicate the impact of the PSD on E_F accurately. Both E_F and simulated E_{PSD} play crucial roles in the correction procedure, allowing for the differentiation of various event classes.

4.2 Corrections

The data correction procedure addresses four main biases of this analysis:

- (i) Gain of peripheral events: this refers to cases where E_F of non-central events is incorrectly reconstructed, leading to them being mistakenly classified as central events;
- (ii) Loss of central events: imperfectness of event reconstruction or presence of off-time interaction/beam particle may lead to the loss of central events;

- (iii) Gain of tracks: imperfectness of the track selection leading to accepting tracks coming from other sources, e.g. gain of tracks coming from weak decays;
- (iv) Loss of tracks: the reconstruction efficiency may lead to the loss of some tracks that should have been included in the analysis.

The influence of off-target interactions is negligible as only very central collisions are considered, and a helium target holder surrounds the target (see Sect. 3).

To address all four biases, a one-dimensional unfolding based on Iterative Bayes' theorem [20] was chosen. For this purpose, the open-access framework RooUnfold [21] was utilized. The one-dimensional unfolding process involves using a response matrix built from Monte Carlo simulations. This matrix allows for the correction of the data histogram to account for the effects of the detector response. To perform the unfolding, a regularization parameter must be specified. It depends on the specific algorithm selected for the unfolding. The choice of this parameter is made in such a way to minimize systematic uncertainties while preserving small statistical uncertainties. In the context of Bayesian unfolding, the regularization parameter corresponds to the number of iterations in the unfolding process. For each beam momentum, the optimal number of iterations in the unfolding procedure was determined through a systematic study. The fluctuation measures were calculated for the unfolded distributions using different numbers of iterations. The final number of iterations was selected such that a further increase in the number of iterations do not cause a significant change in the values of the fluctuation measures. The unfolding procedure involves categorizing events into three distinct types: “good”, “missed”, and “fake” events. These categories may have varying definitions depending on the specific experiments and analysis processes. In this particular study, the definitions are as follows:

Fig. 4 Schematic diagrams indicating by shading the PSD modules used in the online and offline event selection. The trigger is derived from the energy in the central 16 modules (1–16) in blue color. Determination of the PSD energy E_{PSD} uses the green (150A GeV/c), orange (75A, 40A, 30A GeV/c) or all modules (19A, 13A GeV/c) at the respective beam momenta

		29	30	31	32	
44	17	18	19	20	33	
43	28	1	2	3	4	21
		5	6	7	8	
42	27	9	10	11	12	22
		13	14	15	16	
41	26	25	24	23	36	
	40	39	38	37		

T2 trigger

		29	30	31	32	
44	17	18	19	20	33	
43	28	1	2	3	4	21
		5	6	7	8	
42	27	9	10	11	12	22
		13	14	15	16	
41	26	25	24	23	36	
	40	39	38	37		

150A GeV/c

		29	30	31	32	
44	17	18	19	20	33	
43	28	1	2	3	4	21
		5	6	7	8	
42	27	9	10	11	12	22
		13	14	15	16	
41	26	25	24	23	36	
	40	39	38	37		

75A, 40A, 30A GeV/c

		29	30	31	32	
44	17	18	19	20	33	
43	28	1	2	3	4	21
		5	6	7	8	
42	27	9	10	11	12	22
		13	14	15	16	
41	26	25	24	23	36	
	40	39	38	37		

19A, 13A GeV/c

- (i) **Good events:** encompass all inelastic events that successfully pass the event selection criteria, meaning they are properly reconstructed in the TPCs. Additionally, these events must fall within a predefined centrality bin as determined by both E_F and simulated E_{PSD} .
- (ii) **Missed events:** this category includes simulated events that were not successfully reconstructed as they did not meet the event selection criteria. It also includes cases where events are reconstructed and fall within the predefined centrality bin based on E_F but have different centrality when assessed using the simulated E_{PSD} .
- (iii) **Fake events:** consist of correctly reconstructed events that fall within the predefined centrality bin determined by the simulated E_{PSD} but display a different centrality when evaluated using E_F .

The unfolding procedure relies on sufficient statistics of simulated events and a Monte Carlo model that encompasses the data distribution to yield meaningful results. It is crucial that the distribution of reconstructed Monte Carlo events is close

to the entire data distribution. Otherwise, the part of the data that is not represented in Monte Carlo may lead to distortions due to the lack of information in the simulated data. To meet this requirement, a dedicated study was conducted at each beam momentum to determine the centrality of the simulated events, ensuring that reconstructed Monte Carlo multiplicities cover the data. An example of the comparison of the data to Monte Carlo can be found in Fig. 6. Thus, one should remember that the response matrix is not necessarily built on the 1% most central interactions in simulated data but rather on the centrality bin, which covers all scenarios represented in the data. Depending on beam momentum, it varies between 10%, 15%, and 20% most central Ar+Sc collision simulated in EPOS1.99 [22]. The Monte Carlo distributions in the considered centrality windows are close to the data distributions, allowing the application of the unfolding procedure in the considered analysis.

Positively (h^+) and negatively (h^-) charged hadron distributions are unfolded with the means of 1D unfolding. Net-charge ($h^+ - h^-$) can be unfolded in two ways. Either with

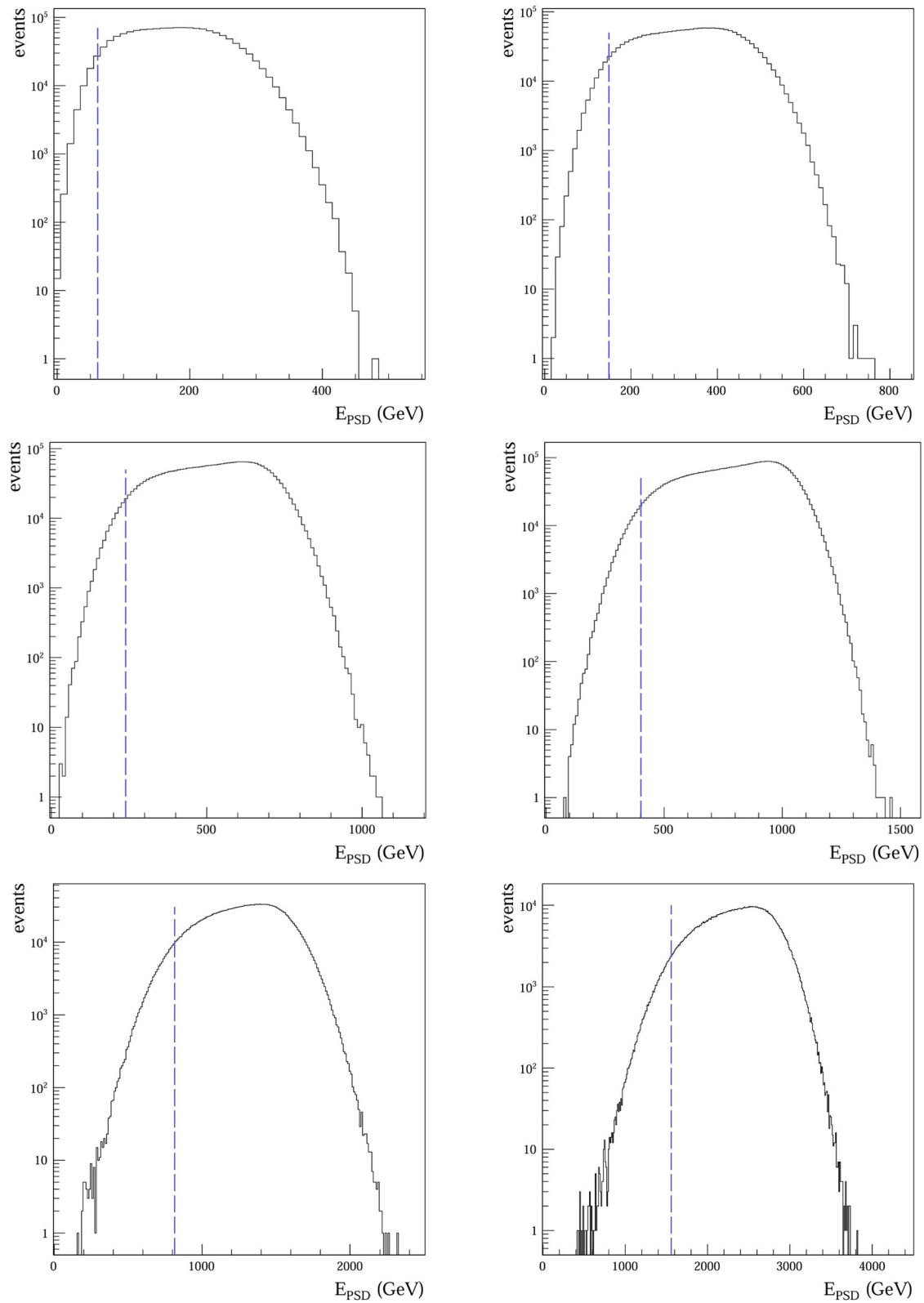


Fig. 5 Event centrality selection using the energy E_{PSD} measured by the PSD calorimeter (for selection of modules see Fig. 4). Distributions show measured E_{PSD} for the T2 selected events for 13A (*top left*) and 19A (*top right*), 30A (*middle left*) and 40A (*middle right*), as well as

75A (*bottom left*) and 150A GeV/c (*bottom right*) beam momenta. The left part of the distribution marked with the vertical line is the region with the 1% most central events

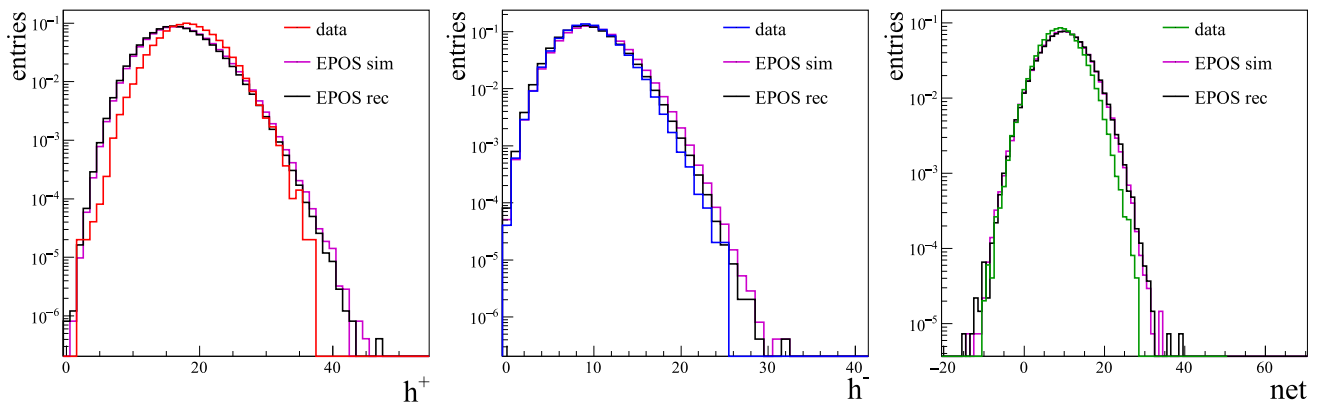


Fig. 6 Positively (*left*) and negatively (*middle*) charged particle multiplicity as well as net-charge (*right*) distributions in measured data (uncorrected) and reconstructed and simulated Monte Carlo in

$^{40}\text{Ar}+^{45}\text{Sc}$ interactions at 13A GeV/c. The data contains the 1% most central events while Monte Carlo centrality is selected according to the procedure described in the text

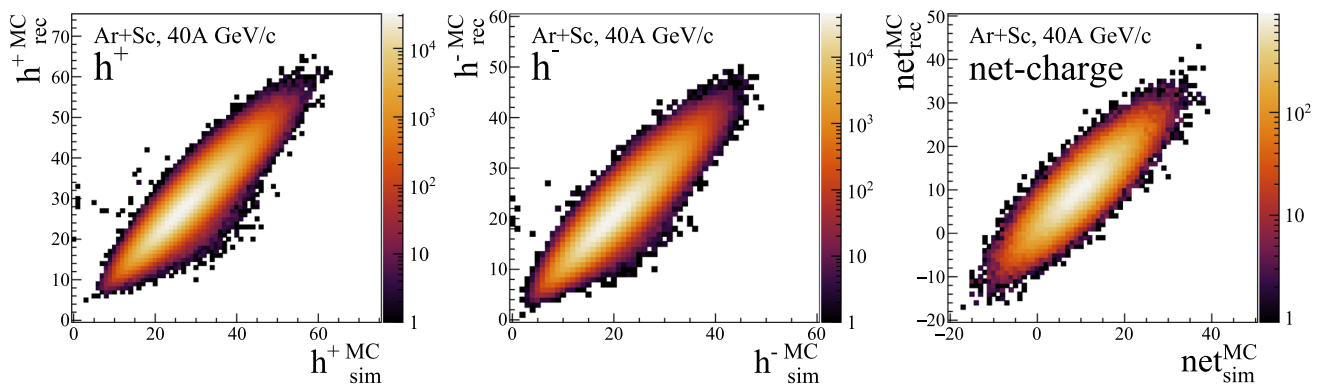


Fig. 7 Relation between Monte Carlo (MC) simulated (sim) and reconstructed (rec) multiplicities for positively (*left*) and negatively (*middle*) charged particles as well as for net-charge (*right*) in $^{40}\text{Ar}+^{45}\text{Sc}$ interactions at beam momentum 40A GeV/c. These multiplicities enter the

response matrix used in the unfolding procedure. Note that the different number of entries between h^+ , h^- , and net-charge arises due to different centrality selections used for the construction of the response matrix

1D unfolding at the level of the final distribution or with the 2D unfolding of h^+ and h^- distribution. Finally, 1D unfolding was used directly on the net-charge distribution, applying the same 0-1% centrality selection for both the measured and Monte Carlo data. The effectiveness of this method was verified by comparing 1D and 2D unfolding results on a smaller system ($p+p$ reactions), confirming that the difference between the two approaches was negligible [23].

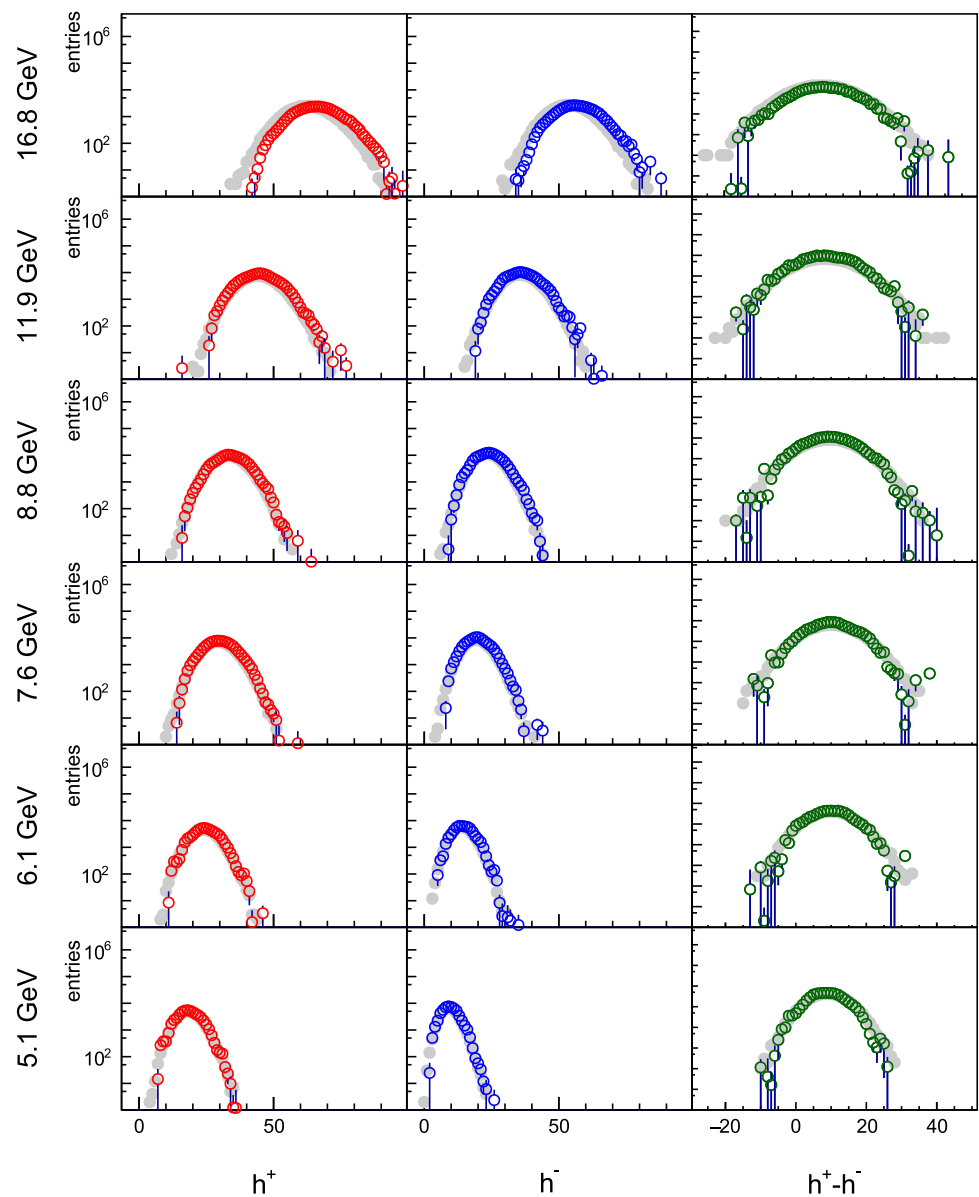
The Monte Carlo model selected as the generator for primary $^{40}\text{Ar}+^{45}\text{Sc}$ interactions is EPOS1.99. The simulation of particle propagation through the detector, including decays and secondary interactions, and the detector response were carried out in the GEANT4 environment [24]. This allowed for the generation of simulated events that closely resembled the actual experimental conditions. The simulated events were then processed through the standard NA61/SHINE reconstruction chain, where the detector signals were reconstructed and tracks were identified. The reconstructed and simulated Monte Carlo multiplicities and net-charge used in

the response matrix for one of the beam momenta are shown in Fig. 7. Measured data distributions, as well as corrected ones, are shown in Fig. 8.

4.3 Statistical uncertainties

The bootstrap method [25] was employed in this study to estimate statistical uncertainties. This approach estimates correlated uncertainties without fragmenting the initial data sample into smaller subsets – a division that would further deplete statistical precision. The core principle underlying the bootstrap method involves generating M samples (referred to as bootstrap samples) from the original data set through sampling with replacement. In this process, each entry from the data set is eligible for inclusion in the bootstrap sample multiple times. The size of each bootstrap sample (representing the distribution of multiplicity or net-charge) corresponds to the size of the original data set. The number of bootstrap iterations was set to $M = 500$. The final uncertainty of a given

Fig. 8 Positively (*left*) and negatively (*middle*) charged hadron multiplicity distributions, as well as net-charge (*right*), for the 1% most central $^{45}\text{Ar}+^{40}\text{Sc}$ collisions at energies $\sqrt{s_{\text{NN}}} = 5.1, 6.1, 7.6, 8.8, 11.9, 16.8$ GeV. The open circles stand for corrected distributions, while the gray, full circles stand for uncorrected ones



intensive quantity corresponds to the standard deviation of the distribution of this quantity derived from M samples. The statistical uncertainties (σ_{stat}) are presented in Table 2.

4.4 Systematic uncertainties

The following effects were included in the estimation of the systematic uncertainty of the results of intensive fluctuation measures presented in this paper:

- (i) The uncertainty arising from the PSD resolution, and consequently the uncertainty associated with centrality selection, was evaluated by manually distorting a measured signal in each PSD module using an empirically obtained formula [26]. The corresponding uncertainty was computed by comparing the intensive fluctuation

measures derived using the actual PSD energy distribution to those obtained using a modified version of the PSD energy distribution and denoted as σ_{PSD} . Notably, the contribution of this effect to the overall systematic uncertainty remains within the bounds of the statistical uncertainty of the results.

- (ii) The removal of the events with off-time beam particles close in time to the trigger particle. The systematic uncertainty of this effect was calculated by changing the time window from $\pm 4 \mu\text{s}$ to $\pm 5 \mu\text{s}$.
- (iii) The uncertainty from the reconstructed vertex z-position cut (used in the same form in the data and the Monte Carlo reconstructed events) was estimated by changing the width of the cut from $\pm 5 \text{ cm}$ to $\pm 9 \text{ cm}$.
- (iv) The uncertainty from the track selection was estimated by removing the impact parameter cut and changing the

Table 2 Numerical values of κ_2/κ_1 , κ_3/κ_2 , κ_4/κ_2 for positively and negatively charged hadrons as well as $\kappa_2[h^+ - h^-]/(\kappa_1[h^+] + \kappa_1[h^-])$, $\kappa_3[h^+ - h^-]/\kappa_1[h^+ - h^-]$, $\kappa_4[h^+ - h^-]/\kappa_2[h^+ - h^-]$ with their sta-tistical and systematic uncertainties, in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ interactions at 13A, 19A, 30A, 40A, 75A, and 150A GeV/c

Beam momentum (A GeV/c)	13	19	30	40	75	150	
$\kappa_2[h^+]/\kappa_1[h^+]$	0.895	0.852	0.901	0.883	0.925	0.875	Result
	0.007	0.007	0.006	0.005	0.007	0.013	σ_{stat}
	0.006	0.011	0.011	0.016	0.019	0.020	σ_{sys}
$\kappa_3[h^+]/\kappa_2[h^+]$	0.674	0.522	0.724	0.419	0.964	1.194	Result
	0.061	0.075	0.073	0.070	0.087	0.196	σ_{stat}
	0.040	0.064	0.055	0.074	0.063	0.116	σ_{sys}
$\kappa_4[h^+]/\kappa_2[h^+]$	− 0.251	0.504	− 1.463	− 1.524	− 1.632	− 1.976	result
	0.573	0.893	0.836	1.061	1.321	3.161	σ_{stat}
	0.092	0.290	1.083	1.730	0.695	5.198	σ_{sys}
$\kappa_2[h^-]/\kappa_1[h^-]$	0.921	0.898	0.938	0.947	0.910	0.832	result
	0.009	0.008	0.007	0.006	0.008	0.013	σ_{stat}
	0.009	0.006	0.012	0.014	0.016	0.031	σ_{sys}
$\kappa_3[h^-]/\kappa_2[h^-]$	1.055	0.914	1.024	0.828	1.221	1.262	result
	0.051	0.059	0.062	0.059	0.078	0.197	σ_{stat}
	0.032	0.071	0.024	0.043	0.064	0.081	σ_{sys}
$\kappa_4[h^-]/\kappa_2[h^-]$	1.231	− 0.055	− 0.217	− 1.023	− 0.209	3.299	result
	0.450	0.557	0.655	0.593	0.893	3.008	σ_{stat}
	0.185	0.468	0.581	0.237	0.832	4.145	σ_{sys}
$\kappa_2[h^+ - h^-]/(\kappa_1[h^+] + \kappa_1[h^-])$	0.691	0.660	0.633	0.619	0.531	0.422	result
	0.007	0.007	0.005	0.004	0.004	0.006	σ_{stat}
	0.018	0.011	0.007	0.004	0.007	0.019	σ_{sys}
$\kappa_3[h^+ - h^-]/\kappa_1[h^+ - h^-]$	0.380	0.487	1.174	0.167	− 0.174	1.233	result
	0.240	0.280	0.317	0.339	0.508	1.172	σ_{stat}
	0.110	0.245	0.152	0.360	0.263	0.595	σ_{sys}
$\kappa_4[h^+ - h^-]/\kappa_2[h^+ - h^-]$	− 0.142	0.105	5.406	1.267	− 0.520	6.491	result
	1.067	1.436	1.692	1.285	1.669	4.514	σ_{stat}
	0.864	1.686	0.854	0.718	0.757	2.884	σ_{sys}

minimum number of reconstructed points to 10 in all TPCs and 10 in the VTPCs.

In the case of effects (ii)–(iv) as they are interdependent, the largest contribution was selected, and denoted as σ_{tl} . The total systematic uncertainties are calculated as:

$$\sigma_{\text{sys}} = \sqrt{\sigma_{\text{PSD}}^2 + \sigma_{\text{tl}}^2}, \quad (6)$$

where σ_{PSD} refers to PSD resolution and σ_{tl} refers to combined effect of remaining effects. The total systematic uncertainties are presented in Table 2.

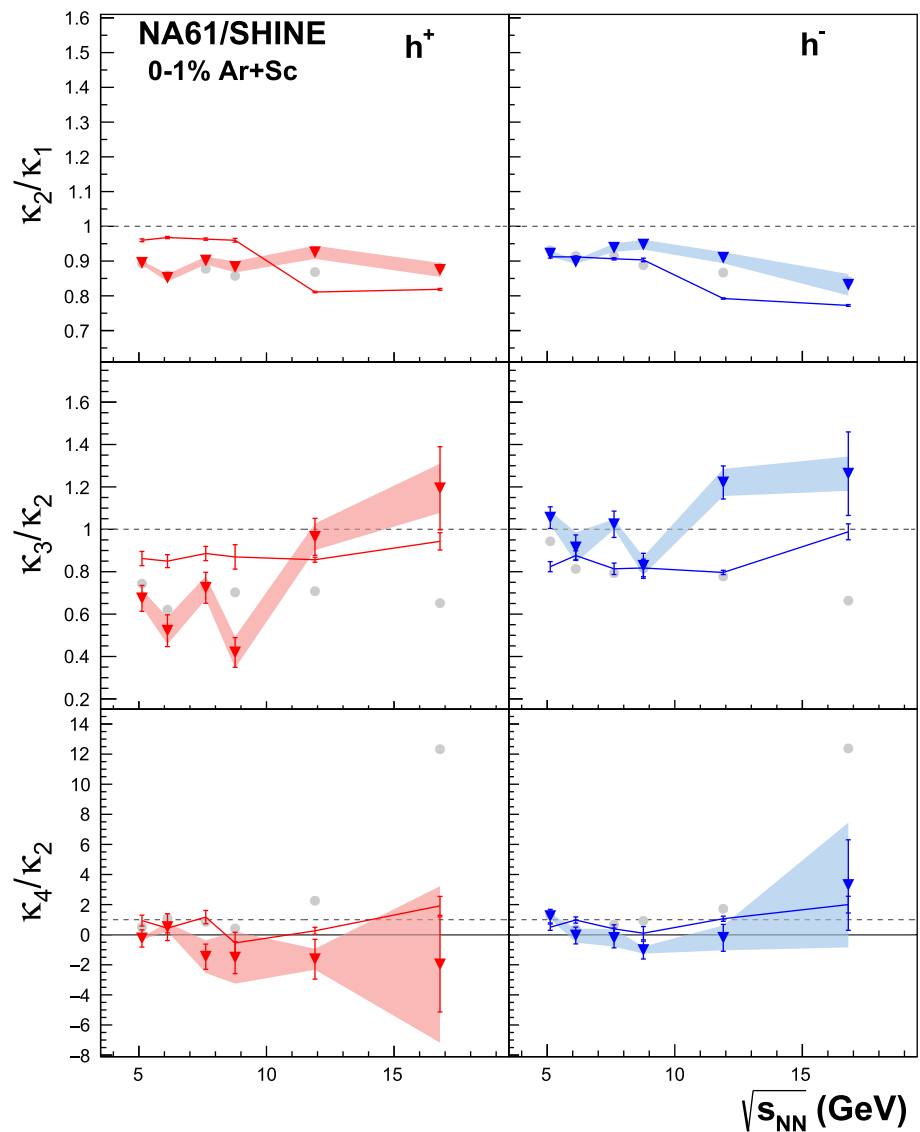
5 Results

The corrected and uncorrected multiplicity distributions of positively and negatively charged hadrons, as well as net-

charge distributions in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ interactions, are presented in Fig. 8.

The energy dependence of corrected and uncorrected intensive quantities κ_2/κ_1 , κ_3/κ_2 , and κ_4/κ_2 for the multiplicity distribution of positively and negatively charged hadrons in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ interactions is depicted in Fig. 9. Deviations from the reference value of unity indicate that obtained distributions deviate from Poisson distribution. The κ_2/κ_1 ratio of h^+ does not indicate any explicit non-monotonic behavior within the extent of systematic uncertainty. For both charges, κ_2/κ_1 is lower than one, indicating that the distribution is narrower than the reference. The ratio κ_3/κ_2 indicates a considerable difference between h^+ and h^- at lower collision energies. In the case of positively charged hadrons, κ_3/κ_2 remains well below one (mostly visible for $\sqrt{s_{\text{NN}}} = 8.8$ GeV). At higher collision energies, it starts to increase up to approximately one. It should be underlined that uncorrected data do not show such changes. The

Fig. 9 The energy dependence of κ_2/κ_1 (top), κ_3/κ_2 (middle), and κ_4/κ_2 (bottom) for positively (left) and negatively (right) charged hadron multiplicity distribution in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ interactions. Color triangles correspond to quantities obtained from corrected distributions, while gray circles correspond to those obtained from uncorrected distributions (statistical uncertainties not indicated). The error bars correspond to statistical uncertainties, while the color bands correspond to systematic uncertainties. The solid color lines show the EPOS1.99 model predictions. The dashed line at unity corresponds to the reference value of the Poisson distribution. The solid line at zero corresponds to the case with no fluctuations in the system



unfolding correction tends to remove peripheral events (see Fig. 8) that are wrongly recognized as central, thus reducing the low multiplicity tail of the distribution. This correction is energy-dependent and hence different for each energy, with the largest effect taking at top energy. In the case of negatively charged hadrons, one can not see such a large deviation from unity. At lower collision energies, κ_3/κ_2 of h^- is close to one and then increases at higher energies. In the case of κ_4/κ_2 of positively charged hadrons, the non-monotonic behavior is absent, yet most energies exhibit a negative sign. On the contrary, the κ_4/κ_2 ratio of negatively charged hadrons stays at or close to zero. The substantial statistical and systematic uncertainties make conclusive interpretations regarding this behavior challenging.

Figure 10 displays the energy dependence of the following intensive quantities: $\kappa_2/(\kappa_1^+ + \kappa_1^-)$, κ_3/κ_1 , κ_4/κ_2 , calculated for the net-charge distributions in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ interactions. The $\kappa_2/(\kappa_1^+ + \kappa_1^-)$ (which is the net-

charge counterpart of κ_2/κ_1 for multiplicity distributions) decreases with the increasing collision energy. It remains below the reference value without changing its sign, which indicates that the measured distribution is narrower than Skellam distribution. The ratios κ_3/κ_1 and κ_4/κ_2 display a hint of non-monotonic behavior with a maximum at $\sqrt{s_{NN}} = 7.6$ GeV, but one should keep in mind considerable associated uncertainties.

The EPOS1.99 predictions for positively and negatively charged hadron multiplicity and net-charge fluctuations in Figs. 9 and 10 are represented by the solid color lines. When examining the ratios of κ_2/κ_1 , EPOS1.99 tends to slightly overestimate h^+ at lower collision energies but underestimates them at higher collision energies. However, EPOS1.99 reasonably describes h^- at lower collision energies and underestimates them at higher collision energies. In the case of κ_3/κ_2 of h^+ EPOS1.99 does not predict energy dependence which is visible in the data. It stays relatively constant, pre-

dicting higher quantity values at lower energy and then lower at higher energies. For negative charge it remains below data signal for the considered energy range (except $\sqrt{s_{NN}} = 8.8$ GeV).

Regarding net-charge, EPOS1.99 is of the same order of magnitude as the experimental results for all considered quantities.

The numerical values of quantities presented in Figs. 9 and 10 are listed in Table 2.

The intensive quantities of charged hadron multiplicities in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ collisions are compared with corresponding quantities in inelastic $p+p$ [23] collisions in Figs. 11 and 12. The track acceptance of both analyses is the same [16]. In the case of $p+p$ reaction, only inelastic interactions were selected. In both analyses, unfolding [21] was used for correction of possible detector biases. The trend is distinct in the case of κ_2/κ_1 for both positively and negatively charged hadron multiplicity. In $p+p$ interactions, this quantity exhibits a consistent monotonic increase with collision energy. On the other hand, in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ interactions, it remains roughly constant or tends to decrease with increasing energy. Furthermore, κ_2/κ_1 in $p+p$ interactions surpasses the reference value of unity at higher collision energies, while in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ interactions, it is below one. The increase of κ_3/κ_2 in both positively and negatively charged hadron multiplicity for $^{40}\text{Ar}+^{45}\text{Sc}$ interactions follows a pattern similar to that observed in $p+p$ collisions. It increases with collision energy but remains not far from the reference value. Notably, a systematic shift towards lower values is observed in $^{40}\text{Ar}+^{45}\text{Sc}$ compared to $p+p$ for positively charged hadrons at lower collision energies. In the case of κ_4/κ_2 , the behavior diverges between $^{40}\text{Ar}+^{45}\text{Sc}$ and $p+p$ interactions. For the majority of collected energies κ_4/κ_2 in $^{40}\text{Ar}+^{45}\text{Sc}$ collisions is below or close to $p+p$ measurements indicating none or weak energy dependence. In contrast, $p+p$ interactions show a slight increase with energy for κ_4/κ_2 of both charge types. It should be underlined that the substantial uncertainties in the $^{40}\text{Ar}+^{45}\text{Sc}$ results complicate the precise assessment of these differences.

The signal magnitudes of $\kappa_2/(\kappa_1^+ + \kappa_1^-)$, κ_3/κ_1 , and κ_4/κ_2 of net-charge in $^{40}\text{Ar}+^{45}\text{Sc}$ interactions within estimated uncertainties are comparable with the signal measured in $p+p$ interactions. In the case of κ_3/κ_1 large statistical uncertainties prevent a more detailed comparison of reactions. Taking into account uncertainties the largest deviation between reactions for κ_4/κ_2 can be observed at $\sqrt{s_{NN}} = 7.6$ GeV. Further studies in Ar+Sc interactions require either increasing the data statistics or finding a more suitable set of quantities that can be utilized in larger centrality bins where volume fluctuations can not be neglected.

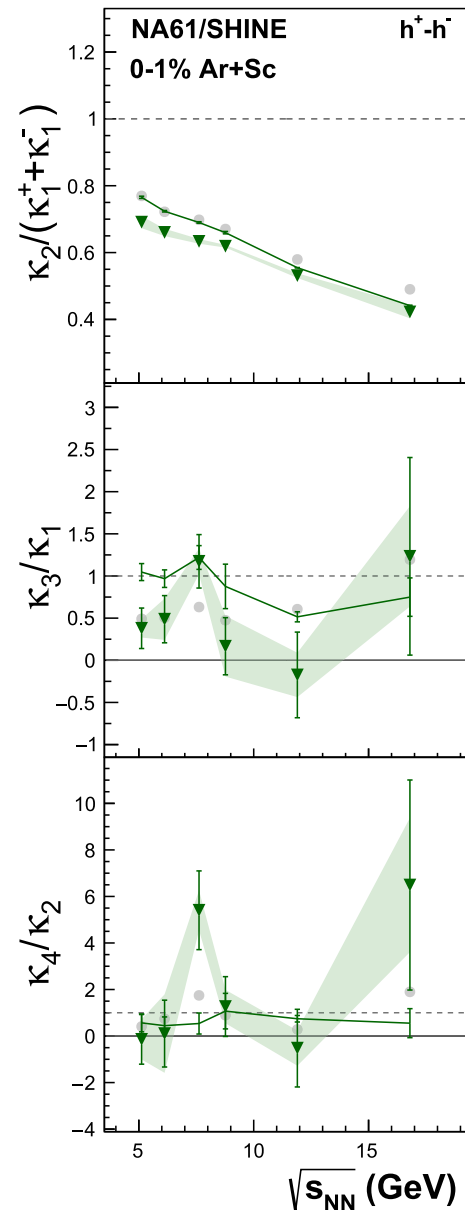
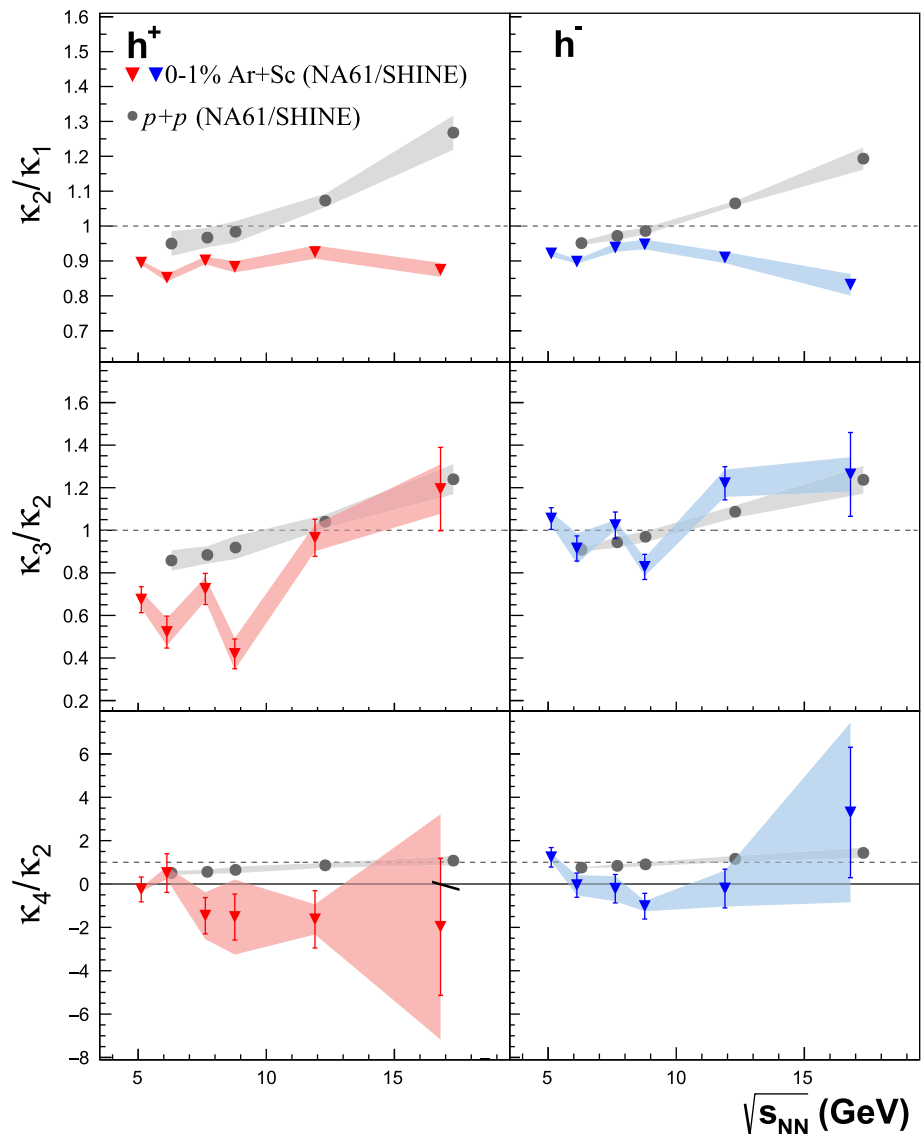


Fig. 10 The energy dependence of $\kappa_2/(\kappa_1^+ + \kappa_1^-)$ (top), κ_3/κ_1 (middle), and κ_4/κ_2 (bottom) of net-charge distribution in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ interactions. Color triangles correspond to quantities obtained from corrected distributions, while gray circles correspond to those obtained from uncorrected distributions (statistical uncertainties not indicated). The error bars correspond to statistical uncertainties, while the color bands correspond to systematic uncertainties. The solid color lines show the EPOS1.99 model predictions. The dashed line at unity corresponds to the reference value of the Skellam distribution. The solid line at zero corresponds to the case with no fluctuations in the system

6 Summary and conclusions

The primary objective of this study was to explore the critical behavior through an examination of fluctuations in mul-

Fig. 11 The energy dependence of κ_2/κ_1 (top), κ_3/κ_2 (middle), and κ_4/κ_2 (bottom) for positively (left) and negatively (right) charged hadron multiplicity distribution in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ (triangles) and inelastic $p+p$ interactions (gray circles) [23]. The error bars correspond to statistical uncertainties, while the color bands correspond to systematic uncertainties. The dashed line at unity corresponds to the reference value of the Poisson distribution. The solid line at zero corresponds to the case with no fluctuations in the system



tiplicity of positively and negatively charged hadrons, as well as net-charge, within the 1% most central collisions of $^{40}\text{Ar}+^{45}\text{Sc}$ reactions at various energies ($\sqrt{s_{\text{NN}}} = 5.1, 6.1, 7.6, 8.8, 11.9, \text{ and } 16.8 \text{ GeV}$). The experimental results refer to cumulant ratios of multiplicity and net-charge distributions of primary charged hadrons resulting from strong interactions and electromagnetic decays in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ collisions within the selected acceptance. They were obtained by correcting measured data using the unfolding technique.

The resulting ratios of cumulants deviate from the Poisson/Skellam distribution indicated by unity for the considered quantities differently than in the case of $p+p$ reactions (except for net-charge $\kappa_2/(\kappa_1^+ + \kappa_1^-)$). In most instances, multiplicity and net-charge distributions appear narrower

than the corresponding Poisson or Skellam distributions. The magnitudes of the measured signal in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ collisions and in $p+p$ are comparable. Only in the case of κ_2/κ_1 of positively and negatively charged hadrons significantly different energy dependence is observed. For comparison, the EPOS1.99 model was employed, known for its alignment with NA61/SHINE results in many cases. Generally, EPOS1.99 indicates similar energy dependence and magnitude of the ratios of cumulants as in measurements performed in $^{40}\text{Ar}+^{45}\text{Sc}$. Further studies in Ar+Sc interactions require either increasing the data statistics or finding a more suitable set of quantities that can be utilized in larger centrality bins where volume fluctuations can not be neglected.

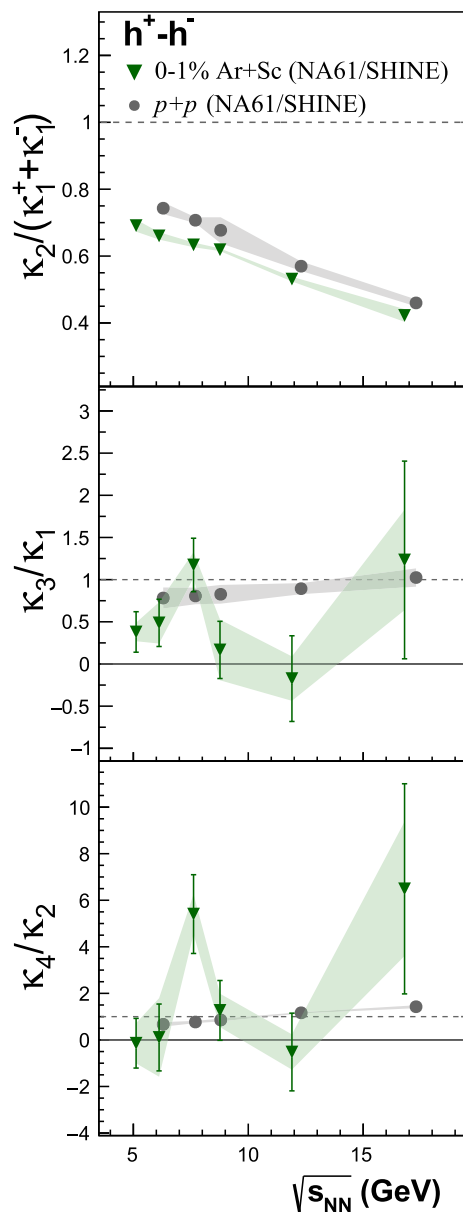


Fig. 12 The energy dependence of $\kappa_2/(\kappa_1^+ + \kappa_1^-)$ (top), κ_3/κ_1 (middle), and κ_4/κ_2 (bottom) of net-charge in the 1% most central $^{40}\text{Ar}+^{45}\text{Sc}$ (triangles) and inelastic $p+p$ interactions (gray circles) [23]. The error bars correspond to statistical uncertainties, while the color bands correspond to systematic uncertainties. The dashed line at unity corresponds to the reference value of the Skellam distribution. The solid line at zero corresponds to the case with no fluctuations in the system

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Code Availability Statement My manuscript has no associated code/software. [Authors’ comment: Code/Software sharing not applicable to this article as no code/software was generated or analysed during the current study.]

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