Abstract

The NA61/SHINE fixed-target experiment at the CERN SPS studies the onset of deconfinement and searches for the critical point of strongly interacting matter by measuring hadron production as a function of the collision energy and the colliding system size.

This contribution summarises recent results on hadron spectra and fluctuations, in particular new results on charged kaon production in $^7\text{Be}+^9\text{Be}$ collisions. Also an overview of the proposed future program of NA61/SHINE is presented.

Keywords: critical point, onset of deconfinement, CERN, SPS

1. Two-dimensional scan program of the NA61/SHINE experiment at CERN SPS

NA61/SHINE scans the phase diagram of strongly interacting matter in baryon density and temperature. The programme is motivated by the evidence for the onset of deconfinement in Pb+Pb collisions at 30A GeV/c found by the NA49 experiment [1, 2]. Measurements of hadron production in a two-dimensional scan in beam momentum (13A–150/158A GeV/c) and system size (p+p, p+Pb, $^7\text{Be}+^9\text{Be}$, Ar+Sc, Xe+La and Pb+Pb) are conducted in parallel to the RHIC beam energy scan. Figure 1 shows the data taking progress.

NA61/SHINE studies the onset of deconfinement by measurements of the hadron spectra and searches for the critical point of strongly interacting matter by measuring event-by-event fluctuations.

The detector is based on a system of five Time Projection Chambers providing acceptance in the full forward hemisphere, down to $p_T = 0$. Time of Flight walls provide additional particle identification. A zero-degree calorimeter, Projectile Spectator Detector, allows the selection of central collisions based on the measurement of the forward energy.

2. Recent results from NA61/SHINE

2.1. Study of the onset of deconfinement

2.1.1. Negatively charged pion spectra

Negatively charged pion spectra in p+p [3], central Be+Be [4, 5] and central Ar+Sc collisions [6, 7, 8] were derived in large acceptance from unidentified negatively charged hadron spectra using the $h^-$ method.
Fig. 1. Data taking progress of the NA61/SHINE two-dimensional scan. The small boxes correspond to $2 \cdot 10^6$ events and the large ones to $50 \cdot 10^6$. The green boxes show data collected as of spring 2017. The reactions planned to be measured within the approved and extended NA61/SHINE programs are shown in red and grey, respectively. The light grey boxes show the large statistics Pb+Pb beam momentum scan planned for 2021–2024.

Fig. 2. Negatively charged pion spectra. Left: Transverse mass spectra at mid-rapidity at 40A GeV/c. An exponential function was fitted in the region $0.2 < m_T < 0.7$ GeV/$c^2$. Right: Rapidity spectra in Ar+Sc collisions at six beam momenta. A sum of two symmetrically displaced normal distributions of independent amplitudes was fitted to the data.
1/2 \[\text{GeV}^{1/2}\]s \approx F_0^{1/2} \quad \langle W \rangle \langle \pi \rangle

\[\langle \pi \rangle \approx F_0^{1/2} \quad \langle W \rangle \langle \pi \rangle \]

**Ar+Sc (NA61 preliminary)**

**Be+Be (NA61 preliminary)**

**p+p (NA61)**

**Au+Au/Pb+Pb (world)**

**p+p (world)**

**Fig. 3.** Energy dependence of the total π multiplicity in full 4π phase space calculated based on π− measurements. The data was divided by the number of wounded nucleons W.

Figure 2 (left) shows the transverse mass spectra at 40A GeV/c, compared with the NA49 results for central Pb+Pb collisions [2]. The spectra are approximately exponential; a deviation from the exponential function at low and high m_T in heavier systems indicates collective radial flow.

The m_T spectra are integrated to derive rapidity spectra, shown for central Ar+Sc collisions at six beam momenta in Fig. 2 (right). The spectra are well described by a sum of two symmetrically displaced normal distributions of independent amplitudes.

Multiplicities of pions of all charges \(\langle \pi \rangle\) are calculated by integrating π− rapidity spectra and using phenomenological dependences between multiplicities of pions of various charges [6]. They are shown in Fig. 3, compared with results from other experiments [9, 10, 11]. The values were divided by the average number of wounded nucleons \(\langle W \rangle\). For higher SPS energies the slope of the energy dependence is larger for the heavy systems (Pb+Pb, Ar+Sc) than for the light ones (p+p, Be+Be). The Statistical Model of the Early Stage (SMES) predicts an increase of the slope at the onset of deconfinement due to the larger number of degrees of freedom in the quark-gluon plasma [12].

### 2.1.2. Charged hadron spectra

\(\pi^+\), p, \(\bar{p}\) (in p+p interactions) and K± (in p+p and central Be+Be collisions) were identified based on measurements of the energy loss in the TPCs (dE/dx) and time of flight in the ToF detectors. Figures 4 and 5 present the energy dependence of the inverse slope parameter of the transverse mass distribution of charged kaons and the ratio of charged kaon to pion multiplicity at mid-rapidity, respectively. The NA61/SHINE results for p+p [13] and Be+Be interactions are compared to those from central Pb+Pb collisions of NA49 [14, 15] and other experiments [16, 17, 18, 19, 20, 21]. For Pb+Pb collisions in the SPS energy range the local plateau (“step”) in the inverse slope parameter visible in Fig. 4 and the peak (“horn”) in the left panel of Fig. 5 were predicted by the SMES as signatures of the onset of deconfinement.

The NA61/SHINE results on p+p and Be+Be interactions greatly improve the quality of the available data on small systems. They also reveal rapid changes of the energy dependence in the SPS energy range suggesting that some properties of hadron production previously attributed to onset of deconfinement in heavy ion collisions are present also in p+p interactions. Interestingly while the inverse slope parameter in Be+Be collisions lies slightly above the one in p+p interactions, the values of the charged kaon to pion ratio are very close in Be+Be and p+p.
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Fig. 4. Energy dependence of the inverse slope parameter of the transverse mass distribution at mid-rapidity for charged kaons. The NA61/SHINE results on p+p interactions (full blue circles) and new results on Be+Be (full green diamonds) collisions are compared with world data on p+p and heavy ion (Pb+Pb and Au+Au) reactions.

Fig. 5. Energy dependence of the positively (left) and negatively (right) charged kaon multiplicity divided by corresponding charged pion multiplicity at mid-rapidity.

Fig. 6. Left: NA61/SHINE measurement of the energy dependence of the ratio of total Λ to π multiplicity in p+p collisions at 40 and 150 GeV/c (full blue circles) compared with world results on p+p and Pb+Pb collisions. Right: NA61/SHINE measurement of the energy dependence the multiplicity ratio K+/π+ in p+p collisions at 20–158 GeV/c (full blue circles) compared with world results on p+p and Pb+Pb collisions.
2.1.3. Lambda spectra

NA61/SHINE measured Λ spectra in p+p interactions at 40 and 158 GeV/c. Figure 6 (left) presents the energy dependence of the ratio of total Λ to π multiplicity, compared with other results for p+p and heavy ion collisions. For Pb+Pb collisions this energy dependence shows a maximum in the SPS energy range for ion collisions but not for p+p reactions. A similar maximum is visible in the ratio of total K+ to π+ multiplicities, shown Fig. 6 (right). The observations for Pb+Pb collisions are consistent with the SMES prediction on the energy dependence of the strangeness to entropy ratio at the onset of deconfinement.

2.2. Search for the critical point

2.2.1. Event-by-event fluctuations

NA61/SHINE searches for the critical point by searching for non-monotonic dependences in event-by-event fluctuations of hadron production properties. Results on two fluctuation measures will be presented:

- Scaled variance of the multiplicity distribution \( \omega[N] = Var(N)/\langle N \rangle \), an intensive variable, insensitive to the system volume (size), but sensitive to volume fluctuations.

- \( \Sigma[P_T, N] \) measure of fluctuations of the transverse momentum and multiplicity, a strongly intensive variable, insensitive both to the system volume and its fluctuations.

Comparison of results of fluctuation measurements between various experiments is challenging due to differences in acceptance, volume fluctuations and choice of measures of fluctuations. For this reason only NA61/SHINE results will be presented in this section.

2.2.2. Multiplicity fluctuations

Figure 7 (left) shows the scaled variance \( \omega[N] \) of the multiplicity distributions for p+p, central Ar+Sc, and Pb+Pb collisions at 150/158A GeV/c calculated in the NA49 acceptance. Only the 0.2% most central Ar+Sc collisions were used in the analysis in order to eliminate volume fluctuations. Results contradict the Wounded Nucleon Model prediction that the values for heavy systems will be greater or equal to those for p+p.
2.2.3. Transverse momentum and multiplicity fluctuations

Figure 8 presents the energy and system size dependence of the $\Sigma[P_T, N]$ measure of transverse momentum and multiplicity fluctuations [8, 25]. The results show no beam momentum dependence. The 5\% increase from p+p to Ar+Sc is consistent with the estimated magnitude of the systematic uncertainty. The Independent Particle Production Model predicts $\Sigma[P_T, N] = 1$, which is consistent with the presented data [26].

2.2.4. Higher order moments of the net-charge distribution in p+p collisions

Higher order moments of multiplicity distributions might be particularly sensitive to effects of a critical point. Figure 9 shows the energy dependence of skewness and kurtosis of the net-charge distribution in p+p interactions [27]. No non-monotonic dependence is observed, but these results establish a reference for future measurements in collisions of heavier systems.
3. NA61/SHINE now and in the future

3.1. NA61/SHINE in 2017–2018

The NA61/SHINE two-dimensional system size and beam momentum scan will be completed with measurements of p+Pb, Xe+La and Pb+Pb collisions in 2017 and 2018. NA61/SHINE with the new small-acceptance Vertex Detector will perform pilot open charm production measurements. Moreover, precise measurements of fluctuations and collective effects in Pb+Pb collisions [28] will be carried out.

3.2. NA61/SHINE in 2021–2024

A detector upgrade of NA61/SHINE is planned during the Long Shutdown 2 at CERN in years 2019–2020: the readout speed will be increased to 1 kHz and a Large Acceptance Vertex Detector will be constructed.

The upgraded detector will allow the performance of a high statistics beam momentum scan with Pb+Pb collisions for precise measurements of open charm and multi-strange hyperon production in 2021–2024. This program will complement future measurements at NICA, FAIR and J-PARC.

NA61/SHINE also conducts extensive and precise particle production measurements for the neutrino physics program which are planned to be continued after 2020.

4. Summary

This contribution discusses recent results from the NA61/SHINE energy and system size scan performed to study the onset of deconfinement and to search for the critical point. Results on particle spectra and fluctuations were presented. New charged kaon spectra in Be+Be collisions at 30A–150A GeV/c were shown. Surprisingly, also p+p reactions show rapid changes in particle production properties, partly resembling those seen in Pb+Pb collisions. Results from Be+Be collisions are close to those from p+p reactions. The charged kaon to pion ratios are consistent and the inverse slope parameters of the transverse mass distributions are marginally higher.

Present results on fluctuations show no indication for non-monotonic dependence and thus no indication for a critical point. Still such features may be revealed in the future results on Xe+La and Pb+Pb collisions.

The presently ongoing two-dimensional scan will be completed in 2018. As an extension of this program NA61/SHINE plans to measure precisely open charm and multi-strange hyperon production in 2021–2024.

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6. References

References

[1] C. Alt, et al., Pion and kaon production in central Pb + Pb collisions at 20A and 30A GeV: Evidence for the onset of deconfinement, Phys. Rev. C77 (2008) 024903. doi:10.1103/PhysRevC.77.024903

[2] S. Afanasiev, et al., Energy dependence of pion and kaon production in central Pb + Pb collisions, Phys. Rev. C66 (2002) 054902. doi:10.1103/PhysRevC.66.054902

[3] N. Abgrall, et al., Measurement of negatively charged pion spectra in inelastic p+p interactions at \( p_{th} = 20, 31, 40, 80 \) and 158 GeV/c, Eur.Phys.J. C74 (2014) 2794. arXiv:1310.2417 doi:10.1140/epjc/s10052-014-2794-6

[4] E. Kaptur, Energy scan with Be+Be collisions: cross-section, centrality determination, pion spectra and mean multiplicities, PoS CPOD2014 (2015) 053.

[5] S. Pulawski, Recent results from NA61/SHINE, Acta Phys. Polon. B46 (11) (2015) 2381. arXiv:1510.07794 doi:10.5506/APhysPolB.46.2381

[6] M. Naskret, Mean pion multiplicities in Ar+Sc collisions in: 10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30-June 4, 2016. arXiv:1611.02396 URL: http://inspirehep.net/record/1496383/files/arXiv:1611.02396.pdf
[7] M. Lewicki, Pion spectra in Ar+Sc interactions at SPS energies in: 10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30–June 4, 2016. [arXiv:1612.01334]
URL http://inspirehep.net/record/1501687/files/arXiv:1612.01334.pdf

[8] K. Grebieszkow, News from strong interactions program of the NA61/SHINE experiment in: 10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30–June 4, 2016. [arXiv:1608.01538]
URL http://inspirehep.net/record/1479456/files/arXiv:1608.01538.pdf

[9] L. Ahle, et al., Particle production at high baryon density in central Au + Au reactions at 11.6-A-GeV/c, Phys. Rev. C57 (1998) 466. doi:10.1103/PhysRevC.57.466

[10] V. Blobel, et al., Higher Moments of the Pion Multiplicity Distribution in Proton Proton Interactions at 12-GeV/c, Nucl. Phys. B103 (1976) 221–233. doi:10.1016/0550-3213(76)90405-6

[11] A. Golokhvastov, Koba-Nielsen-Olesen scaling, Phys.Atom.Nucl. 64 (2001) 84–97. doi:10.1134/1.344946

[12] M. Gazdzicki, M. I. Gorenstein, On the early stage of nucleus-nucleus collisions, Acta Phys.Polon. B30 (1999) 2705. arXiv:hep-ph/9803462

[13] S. Pulawski, Energy dependence of hadron spectra and multiplicities in p+p interactions: A Compilation, Phys.Rev. C69 (2004) 044903. doi:10.1103/PhysRevC.69.044903

[14] M. Gazdzicki, M. I. Gorenstein, M. Mackowiak-Pawlowska, On Normalization of Strongly Intensive Quantities, Phys. Rev. C88 (2013) 024909.

[15] B. Abelev, et al., Production of charged pions, kaons and protons at large transverse momenta in pp and PbPb collisions at √s(NN)=2.76 TeV, Phys.Rev.Lett. 109 (2012) 252301. arXiv:1208.1974. doi:10.1103/PhysRevLett.109.252301

[16] H. Stroebele, New(s) from NA61: A in p+p and π− in Ar+Sc, talk at the 16th International Conference on Strangeness in Quark Matter (SQM 2016) Berkeley, USA, June 27-July 1, 2016 (proceedings to be published), https://indico.cern.ch/event/403915/contributions/2142033/attachments/1300036/1902801/EA_cpod.pdf (2016).

[17] A. Seryakov, Centrality determination and multiplicity fluctuations in Ar+Sc collisions at CERN SPS from NA61/SHINE, arXiv:1501.03720. doi:10.1140/epjc/s10052-016-4003-2

[18] A. Aduszkiewicz, Beam momentum scan with Pb+Pb collisions, Tech. Rep. CERN-SPSC-2015-038. SPSC-P-330-ADD-8, CERN, (Oct 2015). URL https://cds.cern.ch/record/2059811