https://doi.org/10.15407/ujpe71.2.94

A. MARCINEK FOR THE NA61/SHINE COLLABORATION

Institute of Nuclear Physics, Polish Academy of Sciences
(Ul. Radzikowskiego 152, PL-31342 Krakow, Poland; e-mail: antoni.marcinek@ifj.edu.pl)

NEW RESULTS ON $\phi(1020)$ PRODUCTION FROM THE NA61/SHINE EXPERIMENT AT CERN SPS [1]

NA61/SHINE is a multipurpose, fixed-target hadron spectrometer at the CERN SPS. Its research program includes studies of strong interactions as well as reference measurements for neutrino and cosmic-ray physics. A significant advantage of NA61/SHINE over collider experiments is its extended coverage of phase space available for particle production. This includes the entire projectile hemisphere of the collision, with no low-p_T cut-off. The energy and system-size dependence of strangeness production play an essential role in studies of the transition from confined to deconfined matter. With its zero net strangeness and its valence structure composed predominantly of s and $\bar{s}$ valence quarks, the $\phi(1020)$ meson will not be sensitive to strangeness-related effects in a purely hadronic scenario, but will behave like a doubly strange particle in a partonic system. This paper presents the first-ever results on $\phi(1020)$ meson production in intermediate-size systems at the CERN SPS, that is, central Ar + Sc collisions at $\sqrt{s_{NN}}$ = 8.8, 11.9, and 16.8 GeV. The presented results include double-differential rapidity-transverse momentum (y-p_T) distributions, transverse mass (m_T) spectra at midrapidity, p_T-integrated rapidity spectra, mean multiplicities (4π yields), and particle ratios. These are compared to data on Pb + Pb and p + p collisions. A discussion of open and hidden strangeness production enhancement is included. Finally, a comparison with three microscopic models is shown, demonstrating their overall failure to describe these new measurements.

K e y w o r d s: hidden strangeness, heavy ion collisions, ϕ meson.

1. Introduction

The subject of this contribution is preliminary results on $\phi(1020)$ production in central Ar + Sc collisions measured by the NA61/SHINE experiment at the CERN SPS, obtained using the $\phi \to K^+K^-$ decay channel. Associated with the idea that the energy and system-size dependence of strangeness production plays an essential role in studies of the transition from confined to deconfined matter [1], this work has a twofold motivation. First, with its zero net strangeness and its valence structure composed predominantly of s and $\bar{s}$ valence quarks, the $\phi(1020)$ meson is of particular interest for constraining hadron production models: $\phi(1020)$ will not be sensitive to strangeness-related effects in a purely hadronic scenario, but will behave like a doubly strange particle in a partonic system. Second, Ar + Sc holds an intermediate position between earlier-measured minimum bias p + p [2, 3] and central Pb + Pb [4] collisions, thus allowing for an improvement of our knowledge of $\phi(1020)$-related phenomena as a function of system size.

The NA61/SHINE detector [5] is a multipurpose fixed-target spectrometer at the CERN SPS. Over the years the detector has undergone multiple upgrades. Fig. 1 shows its configuration during the Ar + Sc data taking in 2015. Its main components are large-volume Time Projection Chambers (TPCs), two of them (VTPCs) immersed in a magnetic field perpendicular to the beam. This gives NA61/SHINE a significant advantage over collider experiments – an acceptance covering nearly the entire forward c.m.s. hemisphere, down to $p_{\rm T}$ = 0 for charged

C i t a t i o n: Marcinek A. for the NA61/SHINE Collaboration. New results on $\phi(1020)$ production from the NA61/SHINE experiment at CERN SPS. *Ukr. J. Phys.* **71**, No. 2, 94 (2026). https://doi.org/10.15407/ujpe71.2.94.

[1] This work is based on the results presented at the 2025 "New Trends in High-Energy Physics" Conference.

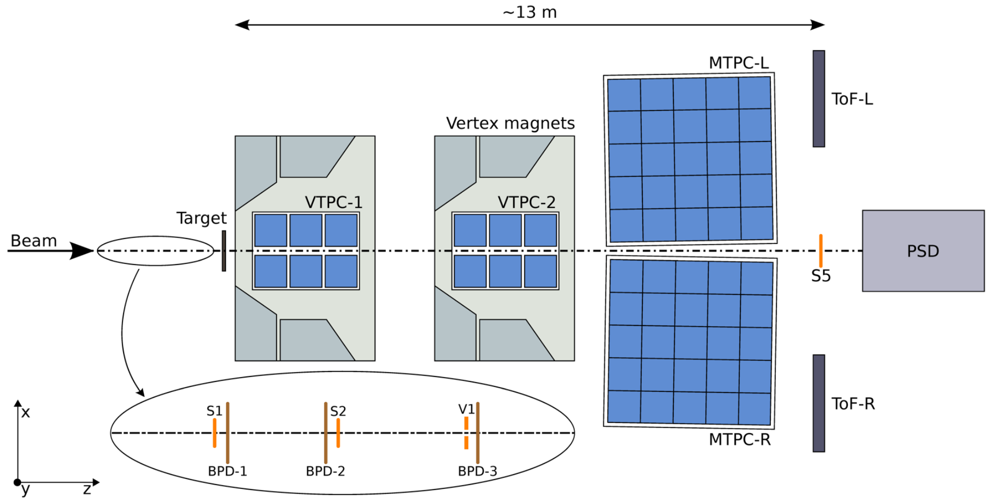


Fig. 1. Schematic layout of the NA61/SHINE detector system (horizontal cut in the beam plane, not to scale) showing the state of the detector during the Ar + Sc data taking in 2015

hadrons. In addition to providing momentum measurement, TPCs also provide particle identification (PID) capabilities using energy loss ($\mathrm{d}E/\mathrm{d}x$) of charged particles in the gas, which is further augmented by time-of-flight measurements in a limited phase-space range. Centrality is measured via the forward energy deposit in a hadronic calorimeter, the Projectile Spectator Detector (PSD).

2. Analysis Methodology

The first step of the analysis is the selection of data. In the case of $\phi(1020)$ analysis in Ar + Sc collisions, the 10% most central events were chosen using the forward energy deposited in the PSD, without pileup, with well measured main vertex, and occurring in the target. Given that $\phi(1020)$ mesons, from an experimental perspective, decay within the main vertex, well reconstructed tracks originating from the main vertex were selected for the analysis, with a sufficient number of points in TPCs to ensure accurate momentum and $\mathrm{d}E/\mathrm{d}x$ measurements.

Special attention was given to particle identification by selecting tracks whose $\mathrm{d}E/\mathrm{d}x$ was inside bands around kaon Bethe–Bloch curve. In earlier analyses [3, 4] a single sample of the kaon candidates was chosen with narrow $\mathrm{d}E/\mathrm{d}x$ cuts to suppress the non-kaon background. Because these cuts also removed a significant amount of kaons, they consequently removed $\phi(1020)$ mesons. This bias was corrected assuming precise knowledge of $\mathrm{d}E/\mathrm{d}x$ distributions for kaons, a method which introduced significant systematic uncertainty. In NA61/SHINE a different approach was chosen [2], using the *tag-and-probe* method [6, 7]. First, for every track an outer band of ±13% of the kaon Bethe–Bloch value was used to suppress non-kaons, without removing any kaons and thus introducing no bias. Second, the actual tag-and-probe method was applied utilizing an inner, biasing, band of ±5% of kaon Bethe–Bloch value. Two samples of oppositely charged kaon candidate pairs were created: in the *tag* sample at least one of the kaon candidates in the pair needed to pass the narrow $\mathrm{d}E\mathrm{d}x$ cut, while in the *probe* sample both candidates had to pass the cut.

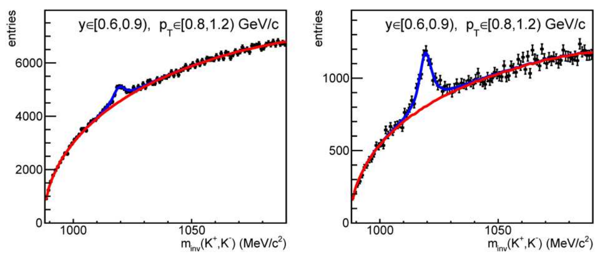
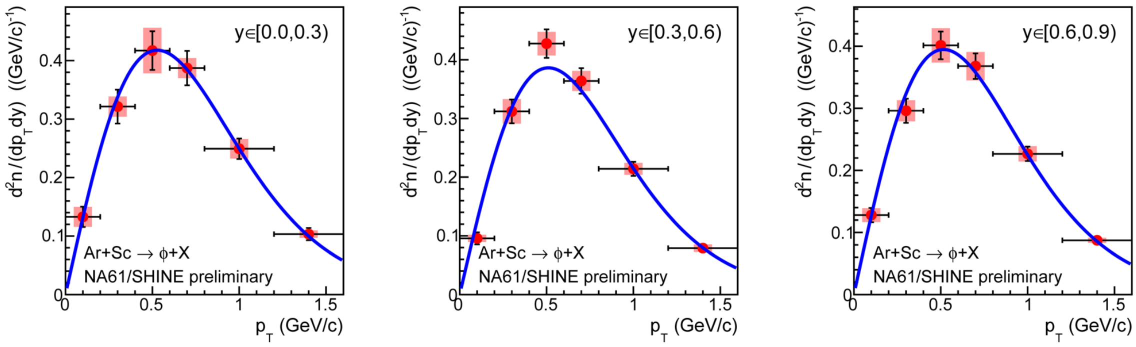


Fig. 2. Illustration of the tag-and-probe method (see text) for one of the analysis bins for Ar + Sc collisions at $\sqrt{s_{NN}} =$ = 16.8 GeV. Left: invariant mass spectrum for the tag sample where at least one of the kaon candidates in the pair is required to pass the strict PID cut. Right: invariant mass spectrum for the probe sample where both kaon candidates in the pair are required to pass the strict PID cut. The red curves represent the fitted background contributions, whereas the blue curves show the sum of the background and signal components



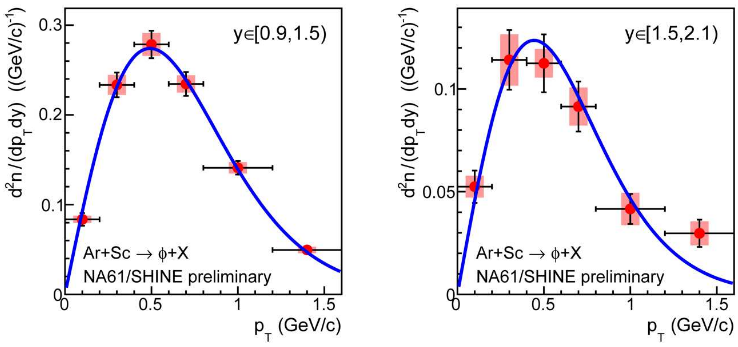


Fig. 3. Double-differential (y, $p_{\rm T}$) spectra of $\phi(1020)$ produced in the 10% most central Ar + Sc collisions at $\sqrt{s_{NN}}$ = 16.8 GeV. Vertical bars represent the statistical uncertainties, red rectangles the systematic uncertainties, and horizontal bars depict the $p_{\rm T}$ bin sizes. Blue curves are fits used to obtain the integrals of the unmeasured tails of the $p_{\rm T}$ spectra to calculate $p_{\rm T}$-integrated dn/dy distributions

The method is illustrated in Fig. 2. To perform the analysis differentially, tag and probe invariant mass spectra were created in bins of pairs' rapidity and transverse momentum. Denoting the unknown efficiency of kaon selection by the narrow cut as ε and the yield of $\phi(1020)$ mesons contributing to the spectra as N_ϕ, the combinatorics of the problem give the following expected signal yields in the two samples:

$$N_t = N_\phi \varepsilon(2-\varepsilon) \text{ and } N_p = N_\phi \varepsilon^2. \tag{1}$$

The tag and probe spectra were fitted simultaneously to obtain N_ϕ. For both samples, the model curve was the sum of signal and background contributions, where the signal was a convolution of relativistic Breit–Wigner function and a q-Gaussian [2] and the background was parametrised as a sum of event mixing and $K^*(892)^0$ templates.

3. Results

Results were obtained for three Ar + Sc collision energies: $\sqrt{s_{NN}}$ = 8.8, $\sqrt{s_{NN}}$ = 11.9, and $\sqrt{s_{NN}}$ = = 16.8 GeV. Fig. 3 shows double-differential (y, $p_{\rm T}$) spectra of $\phi(1020)$ produced in the 10% most central Ar + Sc collisions at $\sqrt{s_{NN}}$ = 16.8 GeV. Similar distributions are also available for the other two collision energies. The $p_{\rm T}$ spectra were fitted for each y bin with thermally motivated functions:

$$f(p_{\rm T}) \propto p_{\rm T} \cdot \exp\left(-\frac{m_{\rm T}}{T}\right), \tag{2}$$

in order to obtain the integrals over the unmeasured tails of the $p_{\rm T}$ spectra to calculate $p_{\rm T}$-integrated dn/dy distributions. These tail contributions were found to be small, not exceeding 5%.

Not constituting an independent result, but rather a different representation of the results described in the previous paragraph, Fig. 4 shows transverse mass spectra of $\phi(1020)$ mesons produced at midrapidity at three Ar + Sc collision energies. The data points were fitted with exponentials to obtain inverse slope parameters of $T = 200 \pm 13 \pm 16$ MeV, $T = 226 \pm 12 \pm 22$ MeV and $T = 246 \pm 12 \pm 8$ MeV for, respectively, $\sqrt{s_{NN}}$ = 8.8, $\sqrt{s_{NN}}$ = 11.9, and $\sqrt{s_{NN}}$ = 16.8 GeV. These values turn out to be comparable to those for charged kaons produced in the same collisions [8], and are larger than those for $\phi(1020)$ mesons measured in p + p reactions (approximately 150 MeV) [2].

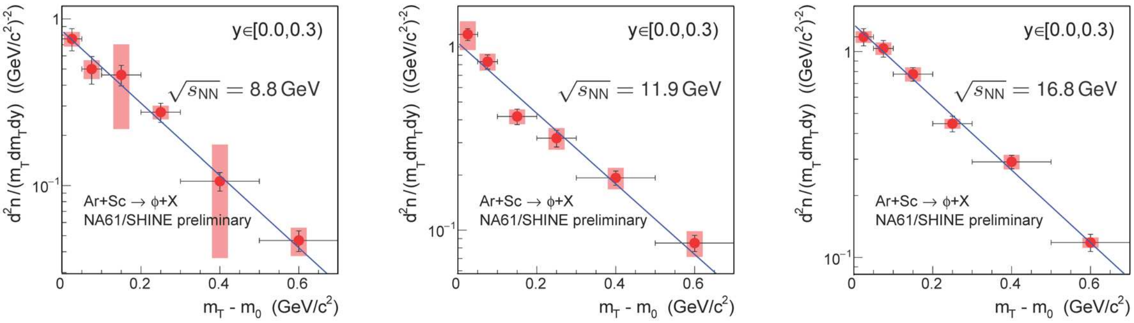


Fig. 4. Transverse mass spectra of $\phi(1020)$ mesons produced at midrapidity in the 10% most central $Ar + Sc$ reactions at three collision energies indicated in the plots. Vertical bars represent statistical uncertainties, red rectangles systematic uncertainties, and horizontal bars depict p_T bin sizes. Blue curves are exponential fits to obtain inverse slope parameters (see text)

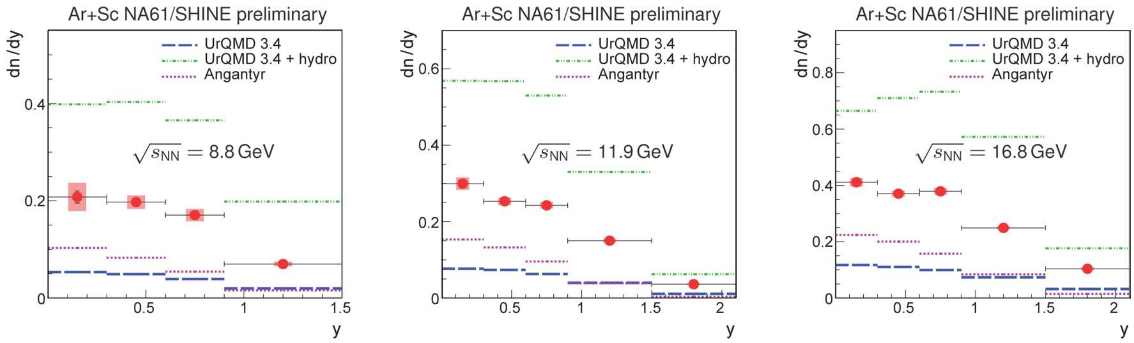


Fig. 5. Rapidity distributions of $\phi(1020)$ mesons produced in the 10% most central $Ar + Sc$ collisions measured by the NA61/SHINE experiment (red circles), compared to the model predictions. Vertical bars represent the statistical uncertainties, red rectangles the systematic uncertainties, and horizontal bars depict the p_T bin sizes. Model calculations were performed by S. Veli (Technical University of Munich) and T. Janiec (The University of Manchester)

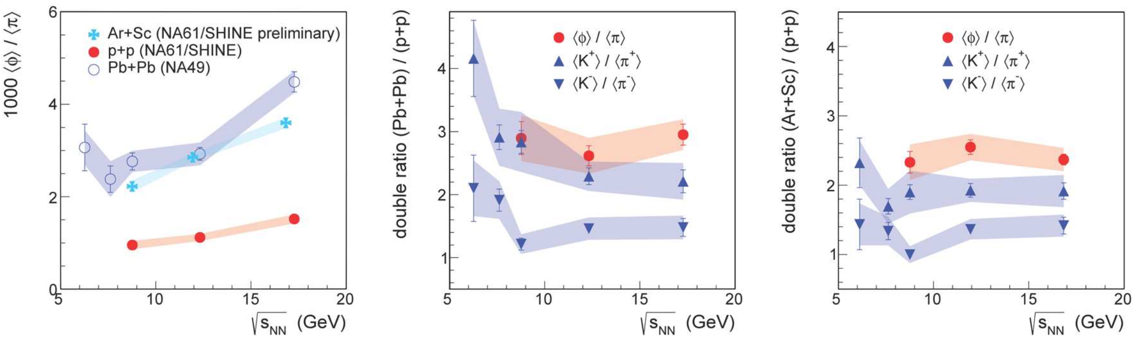


Fig. 6. Left: energy dependence of the ϕ/π ratio for the minimum bias $p + p$ [2], central $Ar + Sc$, and central $Pb + Pb$ [4] collisions. Middle and right: energy dependence of the enhancement of ϕ and charged kaon production relative to pion production in $Pb + Pb$ and $Ar + Sc$ collisions over the $p + p$ reactions. Yields of pions and kaons are taken from [13] for $p + p$ collisions, from [8] for $Ar + Sc$, and from [12] for $Pb + Pb$ reactions. Vertical bars denote statistical uncertainties, while the shaded bands represent the systematic uncertainties

By summing up the measured parts of the double-differential spectra and adding small tail contributions estimated from fits, rapidity distributions were obtained. In Fig. 5 these are compared for the three collision energies to model predictions from two variants of UrQMD [9, 10] and PYTHIA Angantyr [11]. One can see that none of the considered models even comes close to describing the data points, with both the base variant of UrQMD and Angantyr significantly underestimating the data, and UrQMD with hydrodynamics significantly overestimating the $\phi(1020)$ production in $\mathrm{Ar+Sc}$ collisions at CERN SPS energies.

Finally, by summing up the measured parts of the rapidity distributions, adding small (up to 2.5%) tail contributions estimated from double Gaussian fits, and doubling thanks to the approximate backward-forward symmetry of central $\mathrm{Ar+Sc}$ collisions, 4π $\phi(1020)$ yields were obtained for the three collision energies. To remove trivial effects of enlarged collision systems, these were divided by the pion yields calculated as $\langle\pi\rangle = \frac{3}{2}(\langle\pi^+\rangle + \langle\pi^-\rangle)$ [2]. The energy dependence of the resulting ϕ/π ratios for central $\mathrm{Ar+Sc}$ collisions is compared in Fig. 6 to those for the minimum bias $\mathrm{p+p}$ [2] and central $\mathrm{Pb+Pb}$ [4] reactions. One can see that the ϕ/π ratio for $\mathrm{Ar+Sc}$ is comparable to that in $\mathrm{Pb+Pb}$ collisions, where the onset of deconfinement is expected, and much higher than that for $\mathrm{p+p}$ interactions. Next, double ratios showing the enhancement of ϕ/π over $\mathrm{p+p}$ collisions are built for $\mathrm{Ar+Sc}$ and $\mathrm{Pb+Pb}$ collisions and compared to similar double ratios for charged kaons calculated with data from [8, 12, 13]. It is clear, that the $\phi(1020)$ enhancement over $\mathrm{p+p}$ collisions is slightly higher than for charged kaons in both $\mathrm{Ar+Sc}$ and $\mathrm{Pb+Pb}$ reactions, and is independent of the collision energy in the considered range.

4. Summary

Preliminary results on the $\phi(1020)$ meson production in the 10% most central $\mathrm{Ar+Sc}$ collisions at $\sqrt{s_{NN}} = 8.8$, $\sqrt{s_{NN}} = 11.9$, and $\sqrt{s_{NN}} = 16.8$ GeV measured by the NA61/SHINE experiment, were presented. They were obtained using the tag-and-probe method, utilizing the $\phi \to K^+K^-$ decay channel. These are the first-ever results on hidden strangeness production in intermediate-sized systems at CERN SPS. The results include double-differential rapidity and transverse momentum spectra of $\phi(1020)$ mesons, as well as p_{T}-integrated rapidity distributions, transverse mass spectra at midrapidity, and 4π yields. The rapidity distributions were compared to three microscopic models, which fail to reproduce the experimental results. Ratios of $\phi(1020)$ to pion production were considered, showing similar values for $\mathrm{Ar+Sc}$ and $\mathrm{Pb+Pb}$ systems, which are much higher than for $\mathrm{p+p}$ collisions. Finally, hidden and open strangeness production enhancement was discussed, showing that for $\phi(1020)$ it is slightly higher than for charged kaons in both $\mathrm{Ar+Sc}$ and $\mathrm{Pb+Pb}$ reactions, and is independent of the collision energy in the considered range.

This work was supported by the National Science Centre, Poland (grant number 2023/51/D/ST2/02950).

1. M. Gazdzicki, M. Gorenstein, P. Seyboth. Onset of deconfinement in nucleus-nucleus collisions: Review for pedestrians and experts. *Acta Phys. Polon. B* **42**, 307 (2011).
2. A. Aduszkiewicz *et al.* (NA61/SHINE Collaboration). Measurement of ϕ meson production in p+p interactions at 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS. *Eur. Phys. J. C* **80**, 199 (2020).
3. S.V. Afanasiev *et al.* (NA49 Collaboration). Production of ϕ-mesons in $\mathrm{p+p}$, $\mathrm{p+Pb}$ and central $\mathrm{Pb+Pb}$ collisions at $E_{\mathrm{beam}} = 158A$ GeV. *Phys. Lett. B* **491**, 59 (2000).
4. C. Alt *et al.* (NA49 Collaboration). Energy dependence of ϕ meson production in central $\mathrm{Pb+Pb}$ collisions at $\sqrt{s_{NN}} = 6$ to 17 GeV. *Phys. Rev. C* **78**, 044907 (2008).
5. N. Abgrall *et al.* (NA61/SHINE Collaboration). NA61/SHINE facility at the CERN SPS: beams and detector system. *J. Instrumentation* **9**, P06005 (2014).
6. G. Aad *et al.* (ATLAS Collaboration). The differential production cross section of the $\phi(1020)$ meson in $\sqrt{s} = 7$ TeV *pp* collisions measured with the ATLAS detector. *Eur. Phys. J. C* **74**, 2895 (2014).
7. R. Aaij *et al.* (LHCb Collaboration). Measurement of the inclusive ϕ cross-section in *pp* collisions at $\sqrt{s} = 7$ TeV. *Phys. Lett. B* **703**, 267 (2011).
8. H. Adhikary *et al.* (NA61/SHINE Collaboration). Measurements of $\pi^\pm$, $K^\pm$, p and $\bar{p}$ spectra in $^{40}\mathrm{Ar} + ^{45}\mathrm{Sc}$ collisions at $13A$ to $150A$ GeV/c. *Eur. Phys. J. C* **84**, 416 (2024).
9. S. Bass *et al.* Microscopic models for ultrarelativistic heavy ion collisions. *Prog. Part. Nucl. Phys.* **41**, 255 (1998).
10. M. Bleicher *et al.* Relativistic hadron-hadron collisions in the ultra-relativistic quantum molecular dynamics model. *J. Phys. G* **25**, 1859 (1999).
11. C. Bierlich, G. Gustafson, L. Lönnblad, H. Shah. The Angantyr model for heavy-ion collisions in PYTHIA8. *J. High Energy Phys.* **10**, 134 (2018).

12. S.V. Afanasiev *et al.* (NA49 Collaboration). Energy dependence of pion and kaon production in central Pb + Pb collisions. *Phys. Rev. C* **66**, 054902 (2002).
13. A. Aduszkiewicz *et al.* (NA61/SHINE Collaboration). Measurements of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS. *Eur. Phys. J. C* **77**, 671 (2017).

Received 06.12.25

А. Марцінек
від колаборації NA61/SHINE

НОВІ РЕЗУЛЬТАТИ ЩОДО УТВОРЕННЯ $\phi(1020)$ В ЕКСПЕРИМЕНТІ NA61/SHINE У CERN SPS

NA61/SHINE – це багатоцільовий гадронний спектрометр з фіксованою мішенню в CERN SPS. Його дослідницька програма включає дослідження сильних взаємодій, а також еталонні вимірювання для фізики нейтрино та космічних променів. Значною перевагою NA61/SHINE над експериментами на колайдері є його розширене охоплення фазового простору, доступного для утворення частинок. Це включає всю півсферу частинки, що налітає, без відсікання низьких p_{T}. Залежність утворення дивності від енергії та розміру системи відіграє суттєву роль у дослідженнях процесу деконфайнменту. Маючи нульову дивність та валентну структуру, що складається переважно з s та $\bar{s}$ валентних кварків, $\phi(1020)$ мезон не буде чутливим до ефектів, пов'язаних з дивністю, у чисто гадронному сценарії, але поводитиметься як подвійно дивна частинка в партонній системі. У цій статті представлено перші в історії результати дослідження утворення $\phi(1020)$ мезонів у системах проміжного розміру на базі CERN SPS, тобто у центральних зіткненнях Ar + Sc при $\sqrt{s_{NN}}$ = 8,8, 11,9, та 16,8 ГеВ. Представлені результати включають подвійний диференціальний розподіл швидкостей від поперечного імпульсу (y-p_{T}), спектри поперечної маси (m_{T}) при середній швидкості, інтегровані за p_{T} спектри швидкостей, середні множинності (вихід 4π) та співвідношення частинок. Ці результати порівнюються з даними про зіткнення Pb + Pb та p + p. Включено обговорення відкритого та прихованого підсилення утворення дивної матерії. Нарешті, проведено порівняння трьох мікроскопічних моделей, яке демонструє їхню загальну неспроможність описати ці нові вимірювання.

Ключові слова: прихована дивність, зіткнення важких іонів, ϕ-мезон.