Multiplicity dependence of $K^*(892)^0$ and $\phi(1020)$ production in pp collisions at $\sqrt{s} = 13$ TeV

**ALICE Collaboration***

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The striking similarities that have been observed between high-multiplicity proton-proton (pp) collisions and heavy-ion collisions can be explored through multiplicity-differential measurements of identified hadrons in pp collisions. With these measurements, it is possible to study mechanisms such as collective flow that determine the shapes of hadron transverse momentum ($p_T$) spectra, to search for possible modifications of the yields of short-lived hadronic resonances due to scattering effects in an extended hadron-gas phase, and to investigate different explanations provided by phenomenological models for enhancement of strangeness production with increasing multiplicity. In this paper, these topics are addressed through measurements of the $K^*(892)^0$ and $\phi(1020)$ mesons at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV as a function of the charged-particle multiplicity. The results include the $p_T$ spectra, $p_T$-integrated yields, mean transverse momenta, and the ratios of the yields of these resonances to those of longer-lived hadrons. Comparisons with results from other collision systems and energies, as well as predictions from phenomenological models, are also discussed.

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1. Introduction

Recent studies of proton-proton (pp) and proton-lead (p–Pb) collisions at the LHC with high charged-particle multiplicities have shown patterns of behavior that are reminiscent of phenomena observed in heavy nucleus-nucleus (A–A) collisions such as Pb–Pb and Xe–Xe. The systems created in these collisions are compared by classifying events according to the final-state charged-particle multiplicity, which is used as a measure of the “activity” of the event. In small collision systems such as pp and p–Pb, multiplicities range from a few to a few tens of charged particles per unit of rapidity, whereas in large systems (A–A collisions), multiplicities of a few thousand charged particles per unit of rapidity can be produced. As discussed below, measurements of azimuthal anisotropies in particle emission [1–7] (quantified using the Fourier coefficients of azimuthal distributions of produced particles), the multiplicity evolution of hadron $p_T$ spectra [8–11], and $p_T$-differential baryon-to-meson ratios suggest the possibility of collective flow even in small systems. Furthermore, the observed enhancement of strange hadron production [8,9,12] could indicate the production of a quark–gluon plasma (QGP), while the possible suppression of the yields of short-lived resonances [8,11] may suggest the presence of an extended hadronic phase. However, it remains an open question whether the underlying causes of these behaviors are truly the same in small and large collision systems.

In order to investigate this, the ALICE Collaboration has measured the $p_T$ spectra and total yields of identified hadrons as a function of the charged-particle multiplicity in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [10,11,13–15] and pp collisions at $\sqrt{s} = 7$ TeV [8,12,16] for many species, including $\pi^\pm$, $K^\pm$, $K^0_S$, $K^*(892)^0$, $p$, $\phi(1020)$, $\Lambda$, $\Xi^-$, $\Xi^0$, deuterons, and their antiparticles. This paper reports on an extension of these studies: a measurement of the multiplicity evolution of the production of $K^*(892)^0$, $K^0_S$, and $\phi(1020)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV, the highest energy reached by the LHC in runs 1 and 2. The present study takes advantage of a pp data set recorded during Run 2 of the LHC in 2015 with an integrated luminosity of 0.88 nb$^{-1}$ and complements other recent ALICE papers on light-flavor hadron production in the same collision system, both in inelastic collisions [17] and as a function of charged-particle multiplicity [9,18,19]. For the remainder of this paper, the average of $K^0_S$ and $K^0_S$ will be denoted as $K^0$, while the $\phi(1020)$ will be denoted as $\phi$.

The ratios of the yields of strange hadrons to pion yields are observed to be enhanced in A–A collisions relative to minimum bias pp collisions [20–22], with the yields in central A–A collisions being well described by statistical thermal models [23–26]. In central A–A collisions, strangeness is produced from the hadronization of a strangeness-saturated QGP and the relative abundances of hadrons reflect the degree of equilibration of the system. At the LHC, hadron-to-pion yield ratios are observed to increase with the charged-particle multiplicity in pp and p–Pb collisions [8–13]; the magnitude of the change from low to high multiplicity in-
creases with the strangeness content of the hadron. The ratios in high-multiplicity pp and p–Pb collisions reach the values observed in peripheral Pb–Pb collisions and generally follow similar trends as the multiplicity increases from pp to p–A to A–A collisions. Furthermore, the yields of strange particles are consistent between $\sqrt{s} = 7$ and 13 TeV for similar charged-particle multiplicities. These results suggest that the yields of these hadrons depend primarily on the charged-particle multiplicity and are independent of the collision system and energy. This is perhaps a surprising result: pp, p–Pb, and A–A collisions involve different physical processes (e.g. different contributions from jets and multiple partonic interactions) and produce $p_T$ spectra with different shapes. Nevertheless, the total abundances of hadrons, even rare particles like $\Omega^-$ and light nuclei, are consistent across the different collision systems for a given charged-particle multiplicity, suggesting that there may be some underlying similarities between the different collision systems. Comparisons of these different collision systems at similar multiplicities may, for example, help to address the question of whether a QGP might be present even in high-multiplicity pp and p–Pb collisions, or alternatively, whether non-QGP effects might explain behavior seen in A–A collisions.

Several theoretical explanations of the multiplicity evolution of strange-hadron production have been put forward, including canonical suppression, rope hadronization, and core-corona effects. In statistical thermal models of large collision systems, strangeness production is described through the use of a grand canonical ensemble, where strangeness conservation is realized on average across the volume of the system. In the canonical suppression picture, strangeness production in small systems is instead described using a canonical ensemble, requiring the exact local conservation of strangeness within the small volume [8,27,28]. As the size of the system decreases, it makes a transition from the grand-canonical to the canonical description, leading to a decrease in strange-hadron yields with decreasing multiplicity. In the rope-hadronization picture, the larger and denser collision systems form color ropes [29–31], groups of overlapping strings that hadronize with a larger effective string tension. This effect, implemented in models such as DIPSY [32–34], also leads to an increase in the production of strange hadrons with increasing charged-particle multiplicity. Core-corona separation is implemented in a variety of models, including EPOS [35–38] and those described in [39,40]. In these models, the collision is divided into “core” and “corona” regions, with the division determined by the string or parton density. Regions with a density greater than the threshold density become the core, which may evolve as a quark–gluon plasma. This is surrounded by a more dilute corona, for which fragmentation occurs as in the vacuum. Strangeness production is higher in the core region, which makes up a greater fraction of the volume of the larger collision systems. This also results in strangeness enhancement with increasing multiplicity.

The $\phi$ meson is a useful probe for the study of strangeness enhancement. The $\phi$ contains two strange valence (anti)quarks, but has no net strangeness. Its production should therefore not be canonically suppressed, while the production of hadrons with open strangeness (e.g. kaons or $\Xi$) may be canonically suppressed [8]. It has, in fact, been rather difficult to describe enhancement of $\phi$-meson production in a framework that involves canonical suppression [8]. In contrast, in the rope-hadronization or core-corona interpretations, the yields of $\phi$ mesons evolve with multiplicity similarly to particles with open strangeness, leading to an expected increase in the $p_T$–integrated $\phi/p$ ratio with increasing charged-particle multiplicity. Measurements of $\phi$-meson production as a function of the multiplicity may help to distinguish between the various explanations of strangeness enhancement in small systems.

One of the main motivations for studying resonances like $K^0$ and $\phi$ in heavy-ion collisions is to learn more about the properties (temperature and lifetime) of the hadronic phase of the collision. When short-lived resonances (such as $\rho(770)^0$, $K^0$, and $\Lambda(1520)$) decay, their daughters may re-scatter in the hadronic phase, leading to a reduction in the measurable resonance yields; conversely, resonances may also be regenerated due to quasi-elastic scattering of hadrons through a resonance state [41–46]. Centrality-dependent suppression of $\rho(770)^0$, $K^0$, and $\Lambda(1520)$ production was observed in Pb–Pb collisions [47–50], and a hint of $K^0$ suppression was reported for p–Pb collisions [11]. Observations of a similar suppression in high-multiplicity pp collisions (e.g., the $K^0/K$ ratio in pp collisions at $\sqrt{s} = 7$ TeV [8]) might be an indication for a hadronic phase with non-zero lifetime in high-multiplicity pp collisions.

Measurements of identified hadrons can also be used to study collective motion in A–A collisions and to search for similar effects in small collision systems. In non-central A–A collisions, the initial spatial anisotropy in the overlap region of the colliding nuclei results in azimuthally anisotropic pressure gradients in the produced medium, leading to azimuthal anisotropies in particle emission. This anisotropic flow is a manifestation of hydrodynamic behavior in the QGP produced in the A–A collision system. Measurements of azimuthal correlations and anisotropies in particle emission [1–7] also suggest the possibility of collective motion in small collision systems. It was observed that the slopes of hadron $p_T$ spectra increase with increasing multiplicity in pp and p–Pb collisions [8–11], while an enhancement in $p_T$–differential baryon-to-meson ratios (e.g. $p/\pi$ and $K^0_0/$Kratio) is observed at intermediate $p_T$ ($2 \leq p_T \leq 7$ GeV/c). This is at least qualitatively similar to the behavior observed in Pb–Pb collisions [51–54], where the effects can be attributed to a collective expansion of the system. In this interpretation, hadrons receive a momentum boost in the direction transverse to the beam axis, which increases in magnitude with increasing multiplicity and is larger for more massive particles. It should be noted, however, that other effects, including recombinations [55–57], may be able to account for the observed behavior. The increase in the slopes of the $p_T$ spectra is also mirrored in the trend of the measured mean transverse momenta ($\langle p_T \rangle$). In contrast to the yields, which evolve along a continuous trend with multiplicity across different collision systems, the $\langle p_T \rangle$ values of light-flavor hadrons follow different trends in pp, p–Pb, and Pb–Pb collisions [10–12,51], with a faster increase for the smaller systems. The $\langle p_T \rangle$ values in the highest multiplicity pp collisions reach, or in some cases exceed, the $\langle p_T \rangle$ values observed in central Pb–Pb collisions. The increase in $\langle p_T \rangle$ in pp collisions is due to changes in the shape of the $p_T$ spectra at low $p_T$; for $p_T \geq 4$ GeV/c, the shapes of hadron $p_T$ spectra are essentially independent of multiplicity [5,58]. The color reconnection (CR) mechanism [59–63] describes the interconnections and interactions between strings that originate from different multi-parton interactions. It is implemented in various forms, sometimes including the formation of color ropes, in several event generators based on string fragmentation. Color reconnection can also modify the yields of hadron species (e.g. increasing the rate of baryon formation) and can lead to collective flow-like effects, even in small collision systems and in event generators like PYTHIA that do not include QGP formation.

The results reported here will allow the study of $K^0$ and $\phi$ production as functions of both energy and multiplicity in pp collisions. The presented results reach higher values of multiplicity than previously measured in pp collisions and therefore provide important additional information on the production of light-flavor hadrons at LHC energies. This paper is organized as follows. The ALICE detector and the criteria adopted for data selection are described in Section 2. A summary of the data analysis procedure is given in Section 3. The results are presented and discussed in Section 4, followed by a summary and conclusions in Section 5.
Table 1
Charged-particle multiplicity densities at midrapidity (dNch/dη)|η|<0.5 for the INEL > 0 class and the various VOM multiplicity classes [10].

| Class | (dNch/dη)|η|<0.5 |
|-------|---------|
| INEL > 0 | 6.69±0.11 |
| I     | 25.75±0.40 |
| II    | 19.83±0.30 |
| III   | 16.12±0.24 |
| IV    | 13.76±0.21 |
| V     | 12.06±0.18 |
| VI    | 10.11±0.15 |
| VII   | 8.07±0.12 |
| VIII  | 6.48±0.10 |
| IX    | 4.64±0.07 |
| X     | 2.52±0.04 |

2. Event and track selection

The ALICE detector is described in detail in [64,65]. The sub-detectors that are relevant to the analysis described in this paper are the Time Projection Chamber (TPC), the Time-of-Flight detector (TOF), the Inner Tracking System (ITS), the V0 detectors, and the TO detectors. The TPC and ITS are used for tracking and finding the primary vertex, while the TPC and TOF are used for particle identification. The V0 detectors (scintillator arrays) and the TO detectors (arrays of Cherenkov counters) sit on either side of the nominal center of the detector at small angles with respect to the beamline. The V0 detectors are used for triggering and to define the multiplicity estimator at forward rapidities (pseudorapidity ranges −3.7 < η < −1.7 and 2.8 < η < 5.1). The TO detectors provide timing information, including a start signal for the TOF.

The K⁰ and φ mesons are reconstructed from a sample of 5×10⁹ pp collisions at √s = 13 TeV recorded in 2015. The minimum bias trigger required hits in both V0 detectors in coincidence with proton bunches arriving from both directions. Beam-induced background and pile-up events are removed offline; see [9,65] for details. Selected events must also have a primary collision vertex reconstructed with the two innermost layers of the ITS and located within ±10 cm along the beam axis of the nominal center of the ALICE detector. Results in this paper are presented for different event classes corresponding to subdivisions of the “inel > 0” event class, which is defined as the set of inelastic collisions with at least one charged particle in the range |η| < 1 [66]. The INEL > 0 sample is divided into multiplicity classes based on the total charge deposited in both V0 detectors (called the “V0M amplitude”). Thus, the event classes are determined by the number of charged particles at forward rapidities, while the K⁰ and φ yields are measured at midrapidity (|y| < 0.5); this to avoid correlations between the K⁰ and φ yields and the multiplicity estimator. Particle yields, yield ratios, and mean transverse momenta are plotted for different multiplicity classes (which correspond to different centralities for A-A collisions) as functions of the corrected charged-particle multiplicity density at midrapidity (dNch/dη)|η|<0.5, where η is the pseudorapidity in the lab frame. As in [8], the various multiplicity classes are denoted using Roman numerals, with class I (X) having the highest (lowest) multiplicity. See Table 1 for the values of (dNch/dη)|η|<0.5 measured for each VOM multiplicity class.

Since the K⁰ and φ mesons are short-lived (i.e., their lifetimes are of the order of ~10⁻²³ s and their decay vertices cannot be distinguished from the primary collision vertex), they cannot be measured directly by the detector. Instead, they are reconstructed via their hadronic decays to charged pions and kaons: K⁰ → π⁺K⁻ (branching ratio 66.503 ± 0.014%) and φ → K⁺K⁻ (branching ratio 49.2 ± 0.5%) [67]. Charged tracks are selected using a set of standard track-quality criteria, described in detail in [11]. Pions and kaons are identified using the specific ionization energy loss dE/dx measured in the TPC and the flight time measured in the TOF. Where the dE/dx resolution of the TPC is denoted as σTPC, pions and kaons are required to have dE/dx values within 2σTPC of the expected value for p > 0.4 GeV/c, within 4σTPC for 0.3 < p < 0.4 GeV/c, and within 6σTPC for p < 0.3 GeV/c (typically, σTPC ~ 5% of the measured dE/dx value). When a pion or kaon track is matched to a hit in the TOF, the time-of-flight value is required to be within 3σTOF of the expected value (σTOF ~ 80 ps) [68]. These event- and track-selection criteria are varied from their default values and the resulting changes in the yields are incorporated into the systematic uncertainties, which are summarized in Table 2.

3. Data analysis

The K⁰ and φ signals are extracted using the same invariant mass reconstruction method described in [11,17,48]. Invariant mass distributions of unlike-charge πK or KK pairs in the same event are reconstructed after particle identification. The combinatorial background is estimated using multiple methods. In the “like-charge” method, tracks of identical charge from the same event are combined to form pairs. This background is 2√λ−− where n−− and n++ are the number of negative-negative and positive-positive pairs in each invariant mass bin, respectively. In the “mixed-event” method, tracks from one event are combined with oppositely charged tracks from up to 5 other events with similar primary vertex positions and multiplicity percentiles. Specifically, it is required that the longitudinal positions of the primary vertices differ by less than 1 cm and the multiplicity percentiles computed using the V0M amplitude differ by less than 5%. The mixed-event πK (KK) background is normalized so that it has the same integral as the unlike-charge same-event distribution in the invariant mass range 1.1 < mπK < 1.15 GeV/c² (1.05 < mKK < 1.08 GeV/c²). In evaluating the systematic uncertainties, the boundaries of the normalization region for the mixed-event background are varied by ~100 MeV/c² for the K⁰ analysis and ~10 MeV/c² for φ.

After subtraction of the combinatorial background, the invariant mass distribution consists of a resonance peak sitting on top of a residual background of correlated pairs. This correlated background contains contributions from jets, resonance decays in which a daughter is misidentified, and decays with more than two daughters. In the analysis of the φ meson in pp collisions, the signal-to-background ratio is large and the background is observed to vary slowly in the region of the peak. For these reasons, a third approach is also used to describe the background in the φ analysis; the combinatorial background is not subtracted, but is instead parameterized together with the residual background using a function as described below. This has the advantage of providing smaller statistical uncertainties than the other methods.

For pT < 4 GeV/c, all three methods provide good descriptions of the KK background and give φ yields within a few percent of each other. The final φ yields for pT < 4 GeV/c are the averages of those extracted using the three methods of describing the combinatorial background, while the spread among the results for the different methods is incorporated into the systematic uncertainties. As pT increases, the yields of hadrons decreases, along with the magnitudes of all of the combinatorial backgrounds studied. The mixed-event background, which lacks any contribution from correlated pairs, is observed to become smaller than the same-event (like- or unlike-charge) combinatorial backgrounds as pT increases, eventually tending to 0 for pT values higher than the ranges considered here. While the mixed-event background could still be used for the φ analysis for 4 < pT ≤ 8 GeV/c, the two other techniques have smaller statistical fluctuations in this pT range. Consequently, the mixed-event technique is not used for the analysis...
of $\phi$ for $p_T > 4$ GeV/c. The mixed-event technique is the primary method used for the extraction of the $K^{0\text{d}}$ yields; variations of the yield due to the use of a like-charge background are covered by the systematic uncertainties. However, for $p_T < 0.8$ GeV/c in multiplicity class I, the like-charge method is preferred, since it provides a better description of the background. At high $p_T$, the mixed-event background for the $K^{0\text{d}}$ analysis exhibits the same behavior as for $\phi$, but the problems appear at higher $p_T$ values than for $\phi$. The mixed-event technique therefore remains the best available option for this $K^{0\text{d}}$ analysis, even at the high end of the $p_T$ range that was studied.

The invariant mass distributions are fitted with a peak function added to a smooth residual background function. For $K^{0\text{d}}$, the peak is described using a Breit-Wigner function. The mass resolution of the detector for the $\phi \to K^- K^+$ channel is of the same order of magnitude as the $\phi$ width. Therefore, the $\phi$ peak is described using a Voigt function: a convolution of a Breit-Wigner function and a Gaussian which accounts for the mass resolution of the detector. The $K^{0\text{d}}$ and $\phi$ width parameters are by default fixed to their vacuum values; to calculate the systematic uncertainties, these parameters are allowed to vary freely and the $\phi$ resolution parameter is fixed to the values (approximately 1–2 MeV/$c^2$) extracted from the Monte Carlo simulations described below. The residual background is parameterized using a second-order polynomial. To evaluate the systematic uncertainties in the $K^{0\text{d}}$ yields, a third-order polynomial is used instead. For the $\phi$ systematic uncertainties, a first-order polynomial and a function of the form $A + Bm_{KK} + C/m_{KK}^2 = -2M(K^{0\text{d}})$ are used. Here, $A$, $B$, and $C$ are free parameters, $m_{KK}$ is the kaon-kaon pair invariant mass, and $M(K^{0\text{d}})$ is the mass of the $K^{0\text{d}}$. The fits are performed in the invariant mass intervals $0.75 < m_{KK} < 1.07$ GeV/$c^2$ for the $K^{0\text{d}}$ analysis and $0.995 < m_{KK} < 1.09$ GeV/$c^2$ for the $\phi$. The ranges of the fits are varied by $\pm 20$ MeV/$c^2$ for $K^{0\text{d}}$ and $\pm 10$ MeV/$c^2$ for $\phi$; the resulting changes in the yields are included in the systematic uncertainties. Finally, particle yields are extracted by integrating the invariant mass distribution in the peak region ($0.798 \leq m_{KK} \leq 0.994$ GeV/$c^2$ for $K^{0\text{d}}$ and $1.01 \leq m_{KK} \leq 1.03$ GeV/$c^2$ for $\phi$), subtrating the integral of the residual background function under the peak, and adding the yields in the tails of the peak fit function outside the integration region. The systematic uncertainty arising from “signal-extraction”, as quoted in Table 2, covers the aforementioned variations in the combinatorial background, mixed-event normalization region, residual background function, peak function, and fit range. An additional uncertainty originates from the procedure used to match track segments in the ITS with tracks in the TPC. The branching ratio correction for the $\phi$ yield introduces a $1\%$ uncertainty, while the corresponding uncertainty for $K^{0\text{d}}$ is negligible. Uncertainties in the yields due to uncertainties in the material budget of the detector and the cross sections for hadronic interactions in that material are taken from a previous study [11]. The raw particle yields are corrected for the branching ratios, as well as the acceptance and efficiency of the reconstruction procedure. The correction for acceptance and efficiency (denoted as $A \times \epsilon$) is calculated using several different event generators (PYTHIA6 Perugia 2011 tune [69], PYTHIA8 Monash 2013 tune [70], and EPOS-LHC [38]), with particles propagated through a simulation of the detector using GEANT3 [71]. No dependence on the generator is observed and the average $A \times \epsilon$ for the three generators is used in order to reduce statistical fluctuations. This correction is of the same order as reported in [11]. A dependence on multiplicity is observed: for $p_T < 3$ GeV/$c$, $A \times \epsilon$ increases by $\sim 10\%$ from multiplicity class I to class X. In the calculation of $A \times \epsilon$, a weighting procedure is used to account for the fact that (1) $A \times \epsilon$ may vary significantly over the width of a $p_T$ bin in the measured spectrum and (2) the simulated $p_T$ distributions used in the calculation do not necessarily have the same shapes as the measured $p_T$ distributions. In the Monte Carlo simulations, the generated and reconstructed $p_T$ spectra (the denominator and numerator in the $A \times \epsilon$ calculation, respectively) are constructed in narrow $p_T$ bins and then weighted using a fit of the measured $p_T$ spectra. The simulated $p_T$ spectra after this weighting are used to recalculate $A \times \epsilon$ in the wider $p_T$ bins used for the measured $p_T$ spectra. This procedure (also used in [8,9,47,48,50] and others) is repeated until the changes in the correction factor become negligible between iterations; no more than three iterations are needed for the process to converge.

A “signal-loss” correction is also applied, which accounts for $K^{0\text{d}}$ and $\phi$ mesons in non-triggered events. This is evaluated using the same simulations as the acceptance and efficiency. To calculate this correction factor, the simulated resonance $p_T$ spectrum before triggering and event selection is divided by the corresponding $p_T$ spectrum after those selections for each multiplicity class. The signal-loss correction typically deviates from unity by $<1\%$, but can deviate by $\sim 10\%$ at low $p_T$ for the lowest multiplicity class. Different event generators provide different descriptions of the non-triggered component of the various multiplicity classes. Following [9], the PYTHIA6 simulation is used to obtain the central values for this correction, while an uncertainty is evaluated by comparing the central values to those given by PYTHIA8 and EPOS-LHC. Finally, the $p_T$ spectra are normalized by the number of accepted events and corrected as in [9] to account for INEL > 0 events that do not pass the event-selection criteria. This correction, which is calculated using the PYTHIA6 simulation, is most important (24%) for the lowest multiplicity class and is $<1\%$ for high-multiplicity collisions (classes I-VIII).

## 4. Results

The $p_T$ spectra for $K^{0\text{d}}$ and $\phi$ in the various multiplicity classes, as well as the ratios of these spectra to the inclusive INEL > 0 spectrum, are shown in Fig. 1. For $p_T \lesssim 4$ GeV/c the increase in the slopes of the $p_T$ spectra from low to high multiplicity is clearly visible. For higher $p_T$, the spectra in different multiplicity classes all have the same shape, indicating that the processes that change the shape of the $p_T$ spectra in different multiplicity classes are dominant primarily at low $p_T$. A similar behavior was reported for unidentified charged hadrons, $K^0_L$, $\Lambda$, $\Xi$, and $\Omega$ for the same collision system [9,58]. The $p_T$-integrated yields $dN/dy$ and mean transverse momenta ($p_T$) are extracted from the $p_T$ spectra in the different multiplicity classes. For each multiplicity class, the $\phi$ yield is extrapolated to the unmeasured region ($p_T < 0.5$ GeV/$c$) by fitting a Lévy-Tsallis function [72–74] to the measured $p_T$ spectra. For multiplicity class
| \( p_T \) spectra of \( K^0 \) and \( \phi \) in \( p\bar{p} \) collisions at \( \sqrt{s} = 13 \) TeV for different multiplicity classes, scaled by factors as indicated. The lower panels show the ratios of the multiplicity-dependent \( p_T \) spectra to the multiplicity-integrated INEL > 0 spectra (with both linear and logarithmic vertical scales).

**Fig. 1.**

| Ratio to INEL > 0 |
|-------------------|
| \( p_T \) (GeV/c) |
| 0 | 2 | 4 | 6 | 8 | 10 |
| 1 | 1.5 | 2 | 2.5 | 3 | 3.5 |

**Fig. 2.** Mean transverse momenta \( \langle p_T \rangle \) of \( K^0 \) and \( \phi \) as functions of \( dN_{ch}/d\eta|\eta|<0.5 \). Results are shown for \( p\bar{p} \) collisions at \( \sqrt{s} = 13 \) TeV [8], as well as for p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV [11]. The measurements in \( p\bar{p} \) collisions at \( \sqrt{s} = 13 \) TeV are also compared to values from common event generators [33,38,69,70]. Bars represent statistical uncertainties, open boxes represent total systematic uncertainties, and shaded boxes show the systematic uncertainties that are uncorrelated between multiplicity classes (negligible for p–Pb).

\( I(X) \) the extrapolated \( \phi \) yield is 12\% (34\%) of the total yield. \( K^0 \) is measured down to \( p_T = 0 \) and no low-\( p_T \) extrapolation is needed to calculate dN/dy for that particle. The extrapolated yield at high \( p_T \) is negligible for both particles. The \( \langle p_T \rangle \) is evaluated using the mean value of the fit function within each \( p_T \) bin, weighted by the measured yield in each bin. For \( \phi \), the fit function is used to calculate the yield and mean \( p_T \) in the low-\( p_T \) extrapolation region, but this is not needed for \( K^0 \). The sources of systematic uncertainty for the \( p_T \) spectra also contribute to the systematic uncertainties of dN/dy and \( \langle p_T \rangle \), except for the ITS-TPC matching and branching ratio uncertainties, which are \( p_T \)-independent and do not contribute to the uncertainties of the \( \langle p_T \rangle \) values. Additional uncertainties in dN/dy and \( \langle p_T \rangle \) of \( \phi \) are evaluated by varying the fit range and the form of the extrapolation function: Bose-Einstein, Boltzmann, and Boltzmann-Gibbs blast-wave [75] distributions, as well as an exponential in m_\( T \) (where m_\( T \) = \( \sqrt{\not{p}^2 + p^2}/c^2 \) and M is the mass of the particle). The uncertainty in the total \( \phi \) yield due to the extrapolation in class I (X) is 1\% (4.4\%). There is no extrapolation uncertainty for the dN/dy of \( K^0 \). Varying the fit function produces a negligible change in \( \langle p_T \rangle \) for \( K^0 \) and such variations are not included in the systematic uncertainties. The systematic uncertainties on the yield and \( \langle p_T \rangle \) are obtained by varying the parameters used in the default analysis. To investigate whether the changes in the yield dN/dy and \( \langle p_T \rangle \) are correlated between different multiplicity bins, the effect of changing each parameter is simultaneously evaluated for both the minimum bias event class and each individual multiplicity class. The multiplicity-correlated and uncorrelated components of the systematic uncertainties are separated, with the latter being plotted as shaded boxes in Figs. 2-5.

The mean transverse momenta \( \langle p_T \rangle \) for \( K^0 \) and \( \phi \) are shown in Fig. 2 as functions of \( dN_{ch}/d\eta|\eta|<0.5 \) and compared with other ALICE measurements and results from model calculations. The \( \langle p_T \rangle \) values in \( p\bar{p} \) collisions at \( \sqrt{s} = 7 \) TeV [8] and 13 TeV follow approximately the same trend. The \( \langle p_T \rangle \) values of \( K^0 \) and \( \phi \) rise slightly faster as a function of \( dN_{ch}/d\eta|\eta|<0.5 \) in pp collisions than in p–Pb collisions for \( dN_{ch}/d\eta|\eta|<0.5 \); the \( \langle p_T \rangle \) values in pp and p–Pb collisions both rise faster than those in Pb–Pb collisions.
collisions as discussed in [8,11]. The measured $\langle p_T \rangle$ values are compared with five different model calculations: PYTHIA6 (Perugia 2011 tune) [69], PYTHIA8 (Monash 2013 tune, both with and without color reconnection) [70], EPOS-LHC [38], and DIPSY [33]. PYTHIA8 without color reconnection provides an almost constant $\langle p_T \rangle$ as $(dN/dy)_{|y|=0.5}$ increases; this is a very different behavior with respect to the trends measured by ALICE and given by the other model calculations. Turning color reconnection on in PYTHIA8 gives better qualitative agreement with the measurements, although the calculation still somewhat underestimates the $\langle p_T \rangle$ values for hadrons containing strange quarks ($K^0$, $K^0$, $\Lambda$, $\Sigma$, and $\Omega$) [9]. Color reconnection in PYTHIA8 introduces a flow-like effect, resulting in an increase in $\langle p_T \rangle$ values with increasing multiplicity without assuming the formation of a medium that could flow [62]. PYTHIA 6 provides a good description of the $\langle p_T \rangle$ values for $\phi$, but underestimates $\langle p_T \rangle$ for $K^0$. The $\langle p_T \rangle$ values predicted by EPOS-LHC are consistent with the measured values for $\phi$, but slightly below the values for $K^0$. Among the model results obtained for the present work, EPOS-LHC gives the best agreement with the measured data. DIPSY gives a larger increase in $\langle p_T \rangle$ from low to high $(dN/dy)_{|y|=0.5}$ than is actually observed; this discrepancy is greater for the $\phi$ and is also observed for other strange hadrons [9].

The values of $\langle p_T \rangle$ for $K^0$ and $\phi$ are compared with those for $K^0$, (anti)protons, and strange baryons in the same collision system in Fig. 3. In central A–A collisions, a mass ordering of the $\langle p_T \rangle$ values is observed; particles with similar masses (e.g., $K^0$, $p$, and $\phi$) have similar $\langle p_T \rangle$ [11,51]. This behavior has been interpreted as evidence that radial flow could be a dominant factor in determining the shapes of hadron $p_T$ spectra in central A–A collisions. However, this mass ordering breaks down for peripheral Pb–Pb collisions, as well as p–p and pp collisions (see Fig. 7 in [14] and measurements reported in [8,9,18]). In pp collisions at $\sqrt{s} = 13$ TeV, the $\langle p_T \rangle$ values for $K^0$ are greater than those for the more massive proton and $\Lambda$ for the same multiplicity classes. The $\langle p_T \rangle$ values for $\phi$ exceed those for $\Lambda$ and even approach those for $\Xi$, despite the approximately 30% larger mass of the $\Xi$. This could be a manifestation of differences between the $p_T$ spectra of mesons and baryons or different behavior for resonances in comparison to the longer lived particles. In [8], the Boltzmann-Gibbs blast-wave model was used to predict the $p_T$ spectra of light-flavor hadrons based on a combined fit of $\pi^0$, $K^0$, and (anti)proton $p_T$ spectra. This study suggested that strange hadrons ($K^0$, $\Lambda$, $\Sigma$, and $\Omega$) and other light-flavor hadrons might participate in a common radial flow, even in pp collisions, but that $K^0$ and $\phi$ do not follow this common radial expansion (for details of this study, see [8]). The same behavior could result in the violation of mass ordering for $\langle p_T \rangle$ seen at $\sqrt{s} = 13$ TeV. A deviation of the $\langle p_T \rangle$ values of short-lived resonances above the trend for other hadrons could in principle be explained by re-scattering of the resonance-decay daughters during the hadronic phase of the collision, which is expected to be most important at low $p_T$ [41]. However, the strongest re-scattering phenomena occur in central A–A collisions, where no deviation from mass ordering is observed. In addition, such effects would be stronger for the shorter lived $K^0$, than for the $\phi$, which decays predominantly outside the hadronic phase (even in central A–A collisions) and should be minimally affected by re-scattering. On the other hand, the observed violation of mass ordering could be due to differences between baryon and meson $p_T$ spectra. Baryon-to-meson ratios such as $p_T/\Lambda$ and $K^0/\Xi$ are observed [8,10] to be enhanced at intermediate $p_T$ ($\sim 3$ GeV/c), even in pp and p–Pb collisions, while similar enhancement is not observed in meson-to-meson ratios like $K/\pi$. Differences between baryons and mesons have also been observed in the $m_T$ spectra of hadrons measured at RHIC energies [76,77]. For $m_T \geq 1$ GeV/c, meson $m_T$ spectra follow one common trend, while baryons follow a different, more steeply falling trend as a function of $m_T$. Such differences between the shapes of baryon and meson spectra may result in mesons having larger (p)/$\phi$ values than baryons with comparable masses. The breakdown of mass ordering, with $(p_T(p))) < \langle p_T(K^0) \rangle \approx \langle p_T(\Lambda) \rangle < \langle p_T(\phi) \rangle \approx \langle p_T(\Xi) \rangle$, is a common feature of the models shown in Fig. 2. This behavior may be a consequence of hadron production via fragmentation at high $p_T$ or $m_T$; meson formation requires only the production of a quark-antiquark pair, while baryon formation requires a diquark-antidiquark pair [76].

The $p_T$-integrated yields of $\phi$ and $K^0$ are shown in Fig. 4 as functions of $(dN/dy)_{|y|=0.5}$. For both particles, $(dN/dy)$ exhibits an approximately linear increase with increasing $(dN/dy)_{|y|=0.5}$. Results for pp collisions at $\sqrt{s} = 7$ and 13 TeV and for p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV follow approximately the same trends. This indicates that, for a given multiplicity, $K^0$ and $\phi$ production rates do not depend on the collision system or energy. Similar results are seen for strange hadrons [9]. The $(dN/dy)$ values are also compared with those obtained from the same models studied for the discussion of $\langle p_T \rangle$. For the $K^0$, EPOS-LHC and PYTHIA8 without color reconnection give the best descriptions, the other PYTHIA calculations exhibit fair agreement with the measured data, and DIPSY tends to overestimate the $K^0$ yields. The $\phi$ yields tend to be slightly underestimated by EPOS-LHC and slightly underestimated by DIPSY, while the PYTHIA calculations underestimate the $\phi$ yields by about 40%. The selected PYTHIA tunes also underestimate the yields of $\Lambda$, $\Sigma$, and $\Omega$ by similar factors [9]. For these baryons, the EPOS-LHC description becomes less accurate with increasing strangeness content; DIPSY describes the $\Lambda$ and $\Sigma$ yields well, but underestimates the yields of $\Omega$ [9].

The ratios of the $p_T$-integrated particle yields $K^0/\Lambda$, $\phi/\pi$, $\phi/K$, and $\Xi/\phi$ are shown in Fig. 5 as functions of $(dN/dy)_{|y|=0.5}$ [9,18]. Within their uncertainties the ratios in pp collisions at $\sqrt{s} = 7$ and 13 TeV and in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are consistent for similar values of $(dN/dy)_{|y|=0.5}$. There is a hint of a decrease in $K^0/\Lambda$ with increasing $(dN/dy)_{|y|=0.5}$ in all three collision systems; for pp collisions at $\sqrt{s} = 13$ TeV the $K^0/\Lambda$ ratio in the highest multiplicity class is below the low-multiplicity value at the 2.5σ level (considering only the multiplicity-uncorrelated uncertainties). The decrease in $K^0/\Lambda$ in central Pb–Pb collisions [11,48,49] has been attributed to re-scattering of the $K^0$ decay products in the hadronic phase of the collision [46]. It remains an open question whether a decrease in pp collisions could be caused by the same mechanism. EPOS-LHC provides the best description of the $K^0/\Lambda$ ratio in pp collisions at $\sqrt{s} = 13$ TeV. PYTHON and DIPSY

![Fig. 3. Mean transverse momenta for $K^0$ and $\phi$ are compared with those for $K^0$, (anti)protons, $\Lambda$, $\Xi^-$, $\Sigma^-$, and $\Omega^-$ in pp collisions at $\sqrt{s} = 13$ TeV as a function of $(dN/dy)_{|y|=0.5}$ [9,18]. The values for $\Lambda$ in the lowest multiplicity class for $\Xi^-$, $\Sigma^-$, and $\Omega^-$ are shifted horizontally for visibility. Bars represent statistical uncertainties; open boxes represent total systematic uncertainties, and shaded boxes show the systematic uncertainties that are uncorrelated between multiplicity classes.](image-url)
trend to overestimate the ratio for large multiplicities and do not reproduce the apparent decrease with increasing $(dN_{ch}/d\eta)_{|\eta|<0.5}$.

The $\phi/\pi$ ratio gradually increases from the lowest-multiplicity pp collisions to mid-central Pb–Pb collisions. This ratio compares the yields of two mesons with zero net strangeness, one of which has hidden strangeness. The canonical statistical model (CSM) [5] with a chemical freeze-out temperature of 156 MeV predicts that this ratio should have little dependence on the multiplicity, since the $\phi$ would not be subject to canonical suppression. The results of the CSM calculation are inconsistent with the observed trend of the $\phi/\pi$ ratio. For pp collisions at $\sqrt{s} = 13$ TeV, the increasing trend of the $\phi/\pi$ ratio is reproduced fairly well by the EPOS-LHC and DIPSY models, while the PYTHIA calculations underestimate the magnitude of the ratio. The $\phi/K$ ratio also follows a similar trend in the three collision systems. It is fairly constant as a function of $(dN_{ch}/d\eta)_{|\eta|<0.5}$, although there is an apparent small increase with $(dN_{ch}/d\eta)_{|\eta|<0.5}$ from the lowest multiplicities up to $(dN_{ch}/d\eta)_{|\eta|<0.5} \approx 400$. EPOS-LHC somewhat overestimates the $\phi/K$ ratio, but is closer to the measured values than PYTHIA, which significantly underestimates $\phi/K$. While PYTHIA6 and DIPSY underestimate the $\phi/K$ ratio, both results exhibit small increases with increasing multiplicity, which is qualitatively similar to the measured trend. The CSM calculation does not describe the behavior of the measured $\phi/K$ ratio for the $(dN_{ch}/d\eta)_{|\eta|<0.5}$ range spanned by the ALICE pp measurements.

In addition to comparing the yields of $\phi$ to pions and kaons, it may be instructive to compare $\Xi$ and $\phi$. These two particles contain the same number of strange valence (anti)quarks: $\phi$ is a $s\bar{s}$ bound state and $\Xi$ contains two strange valence quarks. However, $\Xi$ would be subject to canonical suppression, unlike the strangeness-neutral $\phi$. Fig. 5 also shows the $\Xi/\phi$ ratio in pp, p–Pb, and Pb–Pb collisions. The ratio increases with increasing $(dN_{ch}/d\eta)_{|\eta|<0.5}$ for low-multiplicity collisions and is then fairly constant for a wide range of multiplicities: from pp and p–Pb collisions at $(dN_{ch}/d\eta)_{|\eta|<0.5} \approx 5$ to central Pb–Pb collisions. There is a possible small increase in the $\Xi/\phi$ ratio from $(dN_{ch}/d\eta)_{|\eta|<0.5}$ at the highest-multiplicity p–Pb collisions, as well as a decrease on the 1.5$\sigma$ level between the p–Pb and Pb–Pb measurements at $(dN_{ch}/d\eta)_{|\eta|<0.5} \approx 50$. Nevertheless, there is no clear increase in the ratio for $(dN_{ch}/d\eta)_{|\eta|<0.5} \geq 7$. The decrease in $\Xi/\phi$ with decreasing $(dN_{ch}/d\eta)_{|\eta|<0.5}$ for low multiplicities could be interpreted as evidence of canonical suppression in small systems; the canonical statistical model predicts a decrease in the $\Xi/\phi$ ratio with decreasing $(dN_{ch}/d\eta)_{|\eta|<0.5}$ that is qualitatively similar to the measured data. However, canonical suppression would also result in an increase in the $\phi/K$ ratio with decreasing $(dN_{ch}/d\eta)_{|\eta|<0.5}$, which is not observed. Given that $\Xi$ and $K$ have different numbers of strange valence (anti)quarks, it is expected that $\Xi$ would be more affected by canonical suppression [8]. It will be interesting to extend the study of the $\phi/K$ ratio to lower multiplicities to test if there is any increase in this ratio due to canonical suppression of kaon yields. The measured multiplicity evolution of the $\Xi/\phi$ and $\phi/K$ ratios suggests that the $\phi$ meson behaves as if it had between 1 and 2 units of strangeness; i.e., $\Xi$ is enhanced more than $\phi$, which is (possibly) enhanced more than $K$. In addition, there are indications of increases in the $p/\pi$ and $K/\pi$ ratios with increasing $(dN_{ch}/d\eta)_{|\eta|<0.5}$ [8,9] which are qualitatively similar to the increase in $\Xi/\phi$, but smaller in magnitude. This suggests that baryon-meson differences (e.g., baryon suppression or meson enhancement) might be a contributing factor, but not the only reason, for the low-multiplicity behavior of the $\Xi/\phi$ ratio. EPOS-LHC, which includes core-corona effects, gives an increasing trend in
$\Sigma/\phi$ with increasing $\langle dN_{ch}/d\eta_{|\eta|<0.5} \rangle$, although the values of the ratio and its flattening at high multiplicity are not particularly well described. In contrast, PYTHIA gives a constant or decreasing value of $\Sigma/\phi$ with increasing $\langle dN_{ch}/d\eta_{|\eta|<0.5} \rangle$, which is inconsistent with the observed trend. DIPSY, which includes rope hadronization, describes the $\Sigma/\phi$ ratio over a wide $\langle dN_{ch}/d\eta_{|\eta|<0.5} \rangle$ range, only failing to describe the decrease in the ratio with decreasing multiplicity for the lowest $\langle dN_{ch}/d\eta_{|\eta|<0.5} \rangle$ values.

The $p_T$ dependence of the particle ratios $K^0/K^0_S$ and $\phi/K^0_S$ is shown in Fig. 6 for low and high multiplicity classes (X and II, respectively). Both ratios increase at low $p_T$ and saturate for $p_T \gtrsim 2.5$ GeV/c; however, for $p_T \lesssim 2.5$ GeV/c the $K^0/K^0_S$ and $\phi/K^0_S$ ratios in the high multiplicity class (II) are less than in the lowest multiplicity class (X). This behavior is qualitatively consistent with observations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [49], where the $K^0/K$ and $\phi/K$ ratios at low $p_T$ in central collisions are lower compared to pp collisions. The decrease in the low-$p_T$ $K^0/K$ ratio in central Pb–Pb collisions with respect to pp collisions is larger than the decrease in the $\phi/K$ ratio, which could be expected due to the presence of re-scattering effects. To quantify the decrease in these particle ratios in pp collisions at $\sqrt{s} = 13$ TeV, the middle panels of Fig. 6 show the double ratios: the high-multiplicity values divided by the low multiplicity values. The double ratios are consistent with unity for $p_T \gtrsim 2.5$ GeV/c, which suggests a common evolution of the $p_T$ spectra for these three mesons. However, for $p_T \lesssim 2.5$ GeV/c, the suppression of the $K^0/K^0_S$ ratio from low to high-multiplicity collisions is greater than the suppression of the $\phi/K^0_S$ ratio. This is quantified in the lower panels of Fig. 6, where the significance of the deviations of the double ratios from unity is shown. For $p_T < 1.2$ GeV/c, the $K^0/K^0_S$ double ratio deviates from unity by 4–6.6 times its standard deviation, while the $\phi/K^0_S$ double ratio deviates from unity at about the 3$\sigma$ level for $0.6 < p_T < 1.4$ GeV/c. This difference may be a hint of re-scattering in small collision systems.

5. Conclusions

The ALICE Collaboration has reported measurements of the $K^0$ and $\phi$ mesons at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV in multiplicity classes. The results have many qualitative similarities to those reported for longer lived hadrons in the same collision system [9,18,19] and are consistent with previous measurements [8] of $K^0$ and $\phi$ in pp collisions at $\sqrt{s} = 7$ TeV. The slopes of the $p_T$ spectra of $K^0$ and $\phi$ are observed to increase with increasing multiplicity for $p_T \lesssim 4$ GeV/c, which is qualitatively similar to the collective radial expansion observed in Pb–Pb collisions, but can also be explained through color reconnection. In contrast, the shapes of the $p_T$ spectra are the same for all multiplicity classes at high $p_T$. Both the $p_T$-integrated yields and the mean transverse momenta increase with increasing charged-particle multiplicity at midrapidity, with approximately linear increases for the yields. It appears that, for a given multiplicity value, the yields of these particles are independent of collision system and energy, while the $(p_T)$ values follow different trends for different collision systems. The mass ordering of the $(p_T)$ values observed in central Pb–Pb collisions is violated in pp collisions, with the $K^0$ and $\phi$ mesons having greater $(p_T)$ than baryons with similar masses. The EPOS-LHC model describes the multiplicity dependence of the yields and $(p_T)$ fairly well for pp collisions at $\sqrt{s} = 13$ TeV. There are hints that the yields of $K^0$ may be reduced, particularly at low $p_T$ and high multiplicity, by re-scattering of its decay daughters in a short-lived hadron-gas phase in pp collisions; similar behavior is observed in Pb–Pb collisions. The $\phi/p$ ratio increases with increasing $\langle dN_{ch}/d\eta_{|\eta|<0.5} \rangle$ and the yields of the $\phi$ meson evolve similarly to particles with 1 and 2 units of open strangeness. The $\phi/K$ and $\Sigma/\phi$ ratios are both fairly constant, exhibiting only slow increases over wide multiplicity ranges, although the $\Sigma/\phi$ ratio decreases with decreasing $\langle dN_{ch}/d\eta_{|\eta|<0.5} \rangle$ for the lowest multiplicity pp and p–Pb collisions. In high-multiplicity pp and p–Pb collisions, these ratios reach values observed in central Pb–Pb collisions. This multiplicity evolution is not consistent with simple descriptions of canonical suppression, but is qualitatively described by the DIPSY model, which includes rope hadronization effects. These new measurements of the $\phi$ provide further constraints for theoretical models of strangeness production in small collision systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] ALICE Collaboration, B. Abelev et al., Multi-particle azimuthal correlations in p- Pb and Pb-Pb collisions at the CERN Large Hadron Collider, Phys. Rev. C 90 (2014) 054901, arXiv:1406.2474.
[2] ALICE Collaboration, S. Acharya, et al., Investigations of anisotropic flow using multi-particle azimuthal correlations in pp, p-Pb, Xe-Xe, and Pb-Pb collisions at the LHC, Phys. Rev. Lett. 123 (2019) 142301, arXiv:1903.01790.
[3] CMS Collaboration, V. Khachatryan et al., Evidence for collectivity in pp collisions at the LHC, Phys. Lett. B 765 (2017) 193–220, arXiv:1606.06198.
[4] ALICE Collaboration, B. Abelev, et al., Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B 719 (2013) 29–41, arXiv:1212.2001.
[5] CMS Collaboration, V. Khachatryan et al., Evidence for collective multi-particle correlations in pp collisions, Phys. Rev. Lett. 115 (2015) 012301, arXiv:1502.05382.
[6] ATLAS Collaboration, G. Aad et al., Observation of long-range elliptic anisotropies in $v_2$ at 13 and 2.76 TeV pp collisions with the ATLAS detector, Phys. Rev. Lett. 116 (2016) 172301, arXiv:1509.04776.
[7] ATLAS Collaboration, M. Aaboud et al., Measurement of multi-particle azimuthal correlations in pp, p-Pb and low-multiplicity Pb-Pb collisions with the ATLAS detector, Eur. Phys. J. C 77 (2017) 428, arXiv:1705.04176.
[8] ALICE Collaboration, S. Acharya et al., Multiplicity dependence of light-flavor hadron production in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. C 99 (2019) 024906, arXiv:1807.11321.
[9] ALICE Collaboration, S. Acharya, et al., Multiplicity dependence of (multi-)strange hadron production in proton-proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 80 (2020) 167, arXiv:1908.01861.
[10] ALICE Collaboration, B. Abelev, et al., Multiplicity dependence of pion, kaon, proton and Lambda production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B 728 (2014) 25–38, arXiv:1307.6796.
[11] ALICE Collaboration, J. Adam, et al., Production of $K^0(892)^0$ and $\phi(1020)$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Eur. Phys. J. C 76 (2016) 245, arXiv:1601.07868.
[12] ALICE Collaboration, J. Adam, et al., Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions, Nat. Phys. 13 (2017) 535–539, arXiv:1606.07642.
[13] ALICE Collaboration, J. Adam, et al., Multi-strange baryon production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B 758 (2016) 389–401, arXiv:1512.07227.
[14] ALICE Collaboration, D. Adamová et al., Production of $\Sigma^+(1385)^0$ and $\Sigma^+(1530)^0$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Eur. Phys. J. C 77 (2017) 389, arXiv:1701.07797.
[15] ALICE Collaboration, S. Acharya et al., Multiplicity dependence of light (anti-)nucleon production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B 800 (2020) 135043, arXiv:1906.01136.
[16] ALICE Collaboration, S. Acharya, et al., Multiplicity dependence of (anti-)deuteron production in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B 794 (2019) 50–63, arXiv:1902.09290.
[17] ALICE Collaboration, S. Acharya, et al., Production of light-flavor hadrons in pp collisions at $\sqrt{s} = 7$ and $\sqrt{s} = 13$ TeV, arXiv:2005.11202 [nucl-ex].
[18] ALICE Collaboration, S. Acharya, et al., Multiplicity dependence of $\pi$, K, and p production in pp collisions at $\sqrt{s} = 13$ TeV, arXiv:2003.02394.
[19] ALICE Collaboration, S. Acharya et al., (Anti-)deuteron production in pp collisions at $\sqrt{s} = 13$ TeV, arXiv:1911.03184.
[20] NA57 Collaboration, F. Antinori et al., Enhancement of hyperon production at central rapidity in 158 A GeV/c Pb-Pb collisions, J. Phys. G 32 (2006) 427–442, arXiv:nucl-ex/0601021.
[21] STAR Collaboration, B.J. Abelev et al., Enhanced strange baryon production in Au+Au collisions compared to p+p at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C 77 (2008) 044908, arXiv:0705.2511.
[22] ALICE Collaboration, B. Abelev et al., Multi-strange baryon production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Lett. B 728 (2014) 116–227, arXiv:1307.5543.
[23] J. Cleymans, I. Kraus, H. Oeschler, K. Redlich, S. Wheaton, Statistical model predictions for particle ratios at $\sqrt{s} = 5.5$ TeV, Phys. Rev. C 74 (2006) 034903, arXiv:hep-ph/0604237.
[24] A. Andronic, P. Braun-Munzinger, J. Stachel, Hadron production in central nucleus nucleus collisions at chemical freeze-out, Nucl. Phys. A 772 (2006) 167–199, arXiv:nucl-th/0511071.
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S. Acharya 141, D. Adamová 94, A. Adler 74, J. Adolffson 80, M.M. Aggarwal 99, G. Aglieri Rinella 33, M. Agnello 30, N. Agrawal 10,53, Z. Ahamed 141, Z. Ahmad 16, S.U. Ahr 76, A. Akindinov 91, M. Al-Turany 106, S.N. Alam 141, D.S.D. Albuquerque 122, D. Aleksandrov 87, B. Alessandro 56, H.M. Alfanda 6, R. Alfarro Molina 71, B. Ali 16, Y. Ali 14, A. Alici 10,26,53, A. Alkin 2, J. Alme 21, T. Alt 58, L. Altenkamper 21, I. Altsybeev 112, M.N. Anaam 6, C. Andre 47, D. Andreou 32, H.A. Andrews 110,

[25] A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, The thermal model on the verge of the ultimate test: particle production in Pb–Pb collisions at the LHC, J. Phys. G 38 (2011) 124081, arXiv:1106.6321.
[26] A. Andronic, P. Braun-Munzinger, K.红lich, J. Stachel, Decoding the phase structure of QCD via particle production at high energy, Nature 551 (2018) 321–330, arXiv:1710.09425.
[27] S. Hamieh, K. Redlich, A. Tounsi, Canonical description of strangeness enhancement from p→Pb–Pb collisions, Phys. Lett. B 486 (2000) 61–66, hep-ph/0002024.
[28] J. Cleymans, A. Forster, H. Oeschler, K. Redlich, F. Uhlig, On the chemical equilibration of strangeness-exchange reactions in heavy-ion collisions, Phys. Lett. B 603 (2004) 146–151, arXiv:hep-ph/0406108.
[29] T.S. Bini et al., H.B. Nielsen, J. Knoll, Colour rope model for extreme relativistic heavy-ion collisions, Nucl. Phys. B 245 (1984) 449–468.
[30] A. Bielas, W. Czyz, Chromoelectric flux tubes and the transverse-momentum distribution in high-energy-nucleus-nucleus collisions, Phys. Rev. D 31 (1985) 198.
[31] N. Arnosto, M.A. Braun, E.G. Ferreiro, C. Pajares, Strangeness enhancement and string fragmentation in nucleus-nucleus collisions, Phys. Lett. B 344 (1995) 301–307.
[32] E. Avaro, G. Gustafson, L. Lønnblad, Small−s dipole evolution beyond the large−s limit, J. High Energy Phys. 10 (2007) 11, arXiv:hep-ph/0610157.
[33] C. Flenberg, G. Gustafson, L. Lønnblad, Inclusive and exclusive observables from dipoles in high energy collisions, J. High Energy Phys. 8 (2011) 103, arXiv:1103.4321.
[34] B. Bierlich, G. Gustafson, L. Lønnblad, A. Tarasov, Effects of overlapping strings in pp collisions, J. High Energy Phys. Phys. Lett. 209 (1988) 90–94.
[35] H.J. Drescher et al., Parton−GBW−Regge theory, Phys. Rep. 350 (2001) 1–93, arXiv:hep-ph/0007198.
[36] K. Werner et al., Event−by−event simulation of the three−dimensional hydro−dynamical evolution from flux tube initial conditions in ultra−relativistic heavy ion collisions, Phys. Rev. C 82 (2010) 044904, arXiv:1004.0895.
[37] K. Werner, B. Guot, I. Karpenko, T. Pierog, Analysing radial flow features in Pb−Pb and p−p collisions at several TeV by studying identified particle production in EPOS3, Phys. Rev. C 85 (2012) 044903, arXiv:1312.1233.
[38] T. Pierog, et al., EPOS LHC test of collective hadronization with LHC data, Phys. Rev. C 92 (2015) 034906, arXiv:1306.0121.
[39] Y. Kanakubo, M. Okai, Y. Tachibana, T. Hiranm, Enhancement of strange baryons in high−multiplicity proton−proton and proton−nucleus collisions, Prog. Theor. Exp. Phys. 2018 (2018) 120101, arXiv:1802.10729.
[40] Y. Akamatsu et al., Dynamically integrated transport approach for heavy−ion collisions at high baryon density, Phys. Rev. C 98 (2018) 024909, arXiv:1805.09624.
[41] M. Bleicher, H. Stöcker, Dynamics and freeze−out hadron resonances at RHIC, J. Phys. G 30 (2004) S111–S118, arXiv:hep-ph/0312278.
[42] G. Torrieri, J. Rafelski, Strangeness hadron resonances as a signature of freeze−out dynamics, Phys. Lett. B 509 (2001) 239−245, arXiv:hep-ph/0103149.
[43] C. Marsiske, R. Bellwied, J. Vites, Formation and decay of hadronic resonances in the QGP, Adv. Nucl. Phys. 31, B 669 (2008) 92−97, arXiv:0807.1569.
[44] S. Vogel, J. Aichelin, M. Bleicher, Resonances as a possible observable of hot and dense nuclear matter, J. Phys. C 37 (2010) 094046, arXiv:1001.3260.
[45] M. Bleicher, J. Aichelin, Strange resonance production: probing chemical and thermal freeze−out in relativistic heavy−ion collisions, Phys. Lett. B 530 (2002) 81−87, arXiv:hep-ph/0201123.
[46] A.G. Knope et al., Hadronic resonance production and interaction in high−energy hadron–hadron collisions at the LHC, Phys. Rev. C 92 (2015) 014911, arXiv:1505.07895.
[47] ALICE Collaboration, S. Acharya et al., # collisions in pp and Pb−Pb collisions at √sNN = 2.76 TeV, Phys. Rev. C 99 (2019) 064901, arXiv:1805.04365.
[48] ALICE Collaboration, B. Abelev et al., K*(892) 0 and φ(1020) production in Pb−Pb collisions at √sNN = 2.76 TeV, Phys. Rev. C 91 (2015) 024909, arXiv:1404.0495.
[49] ALICE Collaboration, J. Adam et al., K*(892) 0 and φ(1020) production at high transverse momentum in pp and Pb–Pb collisions at √sNN = 2.76 TeV, Phys. Rev. C 95 (2017) 064606, arXiv:1702.00555.
[50] ALICE Collaboration, S. Acharya et al., Suppression of Λ(1520) production in central Pb–Pb collisions at √sNN = 2.76 TeV, Phys. Rev. C 99 (2018) 024905, arXiv:1805.04361.
[51] ALICE Collaboration, B. Abelev et al., Centrality dependence of Σ, Π, K, and p production in Pb–Pb collisions at √sNN = 2.76 TeV, Phys. Rev. C 88 (2013) 044910, arXiv:1303.0771.

ALICE Collaboration

S. Acharya 141, D. Adamová 94, A. Adler 74, J. Adolffson 80, M.M. Aggarwal 99, G. Aglieri Rinella 33, M. Agnello 30, N. Agrawal 10,53, Z. Ahamed 141, Z. Ahmad 16, S.U. Ahr 76, A. Akindinov 91, M. Al-Turany 106, S.N. Alam 141, D.S.D. Albuquerque 122, D. Aleksandrov 87, B. Alessandro 56, H.M. Alfanda 6, R. Alfarro Molina 71, B. Ali 16, Y. Ali 14, A. Alici 10,26,53, A. Alkin 2, J. Alme 21, T. Alt 58, L. Altenkamper 21, I. Altsybeev 112, M.N. Anaam 6, C. Andre 47, D. Andreou 32, H.A. Andrews 110,
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