I. INTRODUCTION

Hot nuclear matter created in ultrarelativistic heavy-ion collisions exhibits its properties through the collective expansion of the fireball. In addition to the longitudinal flow which is largely set by the initial conditions, pressure gradients drive strong expansion also perpendicularly to the collision axis. Due to expansion and cooling the fireball eventually arrives to the state where it disintegrates. This is the moment when most abundant hadrons obtain their observed momenta and momentum spectra are frozen-out. In fact, it does not happen instantaneously for all hadrons. Freeze-out is a continuous process.

It is useful to describe the freeze-out state of the fireball by hydrodynamically inspired parametrisations. They usually assume that freeze-out happens instantaneously along some hypersurface. The models include locally thermalized momentum distribution and some pattern of longitudinal and transverse expansion flow velocity. A few parametrisations are on the market which differ in details of the assumptions for the density and velocity profiles or the exact shape of the freeze-out hypersurface. In our analysis we shall make use of the so-called blast-wave model.

An important part of final state hadrons does not originate directly from the fireball but comes from decays of unstable resonances which themselves were emitted from the fireball. Hadron production by resonance decays is clearly substantial for pions. However, it also contributes largely also to protons and kaons, as we will show below. In spite of this, it is often omitted in calculations and analyses due to its computational complexity. We fit the single-hadron transverse-momentum spectra measured in Pb+Pb collisions at √sNN = 2.76 TeV with the blast-wave model that includes production via resonance decays. Common fit to pions, kaons, (anti)protons, and lambdas yields centrality dependence of the freeze-out temperature and transverse expansion velocity. In the most central collisions we see T = 98 MeV and ⟨v1⟩ = 0.654. The K⁺ resonance fits into this picture but the φ meson might freeze-out a little earlier. Multistrange baryons seem to decouple at higher temperature and weaker transverse flow. Within our model we observe hints of chemical potential for the charged pions.

II. THE MODEL

Our analysis is performed in the framework of the blast-wave model, which is characterised by its emission function. Formally, this is the Wigner phase-space density of the source of hadrons of type i

\[ S(x,p) d^4x = g_i \frac{m_i \cosh(\eta - y)}{(2\pi)^3} \times \left( \frac{p_i u^\mu - \mu_i}{T} + s_i \right)^{-1} \theta \left( 1 - \frac{r}{R} \right) \times r \, dr \, d\phi \, \delta(\tau - \tau_0) \tau \, d\tau \, d\eta. \]
Because of the dominant expansion in the longitudinal direction one uses longitudinal proper time \( \tau = \sqrt{t^2 - z^2} \) and space-time rapidity \( \eta = \frac{1}{2} \ln((t+z)/(t-z)) \). Polar coordinates \( r, \varphi \) are used in the transverse plane. We use proper quantum statistical distributions with \( s_i = 1 \) (-1) for fermions (bosons) and \( g_i \) is the spin degeneracy. Every isospin state is treated separately. This prescription assumes sharp freeze-out along the hypersurface \( \tau = \tau_0 \) and uniform density distribution within the radius \( R \). This means that our freeze-out time does not depend on radial coordinate\(^1\). The expansion of the fireball is represented by the velocity field

\[
u^\mu = (\cosh \eta, \cosh \eta, \sinh \eta \cos \varphi, \sinh \eta \sin \varphi, \cosh \eta, \sinh \eta) \tag{2}\]

where the transverse velocity is such that

\[
\nu_t = \tanh \eta_t = \eta_f \left( \frac{r}{R} \right)^n . \tag{3}\]

In relation \( \eta_f \) parametrises transverse flow gradient and \( n \) the profile of the transverse velocity. The mean transverse velocity is then

\[
\langle \nu_t \rangle = \frac{2}{n + 2} \eta_f . \tag{4}\]

The transverse size \( R \) and the freeze-out proper time \( \tau_0 \) influence total normalizations of transverse momentum spectra. However, in this study we ignore those and hence we have no sensitivity to these geometric parameters.

From the emission function, spectrum of directly produced hadrons is obtained as

\[
E^2 d^3N \left( d^3x \right) = \int S(x,p) \, d^4x , \tag{5}\]

where the integration runs over the whole freeze-out hypersurface. If one replaces the quantum-statistical distribution in eq. (1) by the classical Boltzmann distribution and performs some of the integrations in eq. (5), one arrives at

\[
E \frac{d^3N}{dp^3} = \frac{m_t \tau_0}{2 \pi^2} e^{\mu_t/T} \times \int_0^R r I_0 \left( \frac{p_t}{T} \sinh \eta_t(r) \right) K_1 \left( \frac{m_t}{T} \cosh \eta_t(r) \right) \, dr \; . \tag{6}\]

This formula is rather easy to evaluate and thus it is often used in spectra fitting.

Resonances are emitted as described by the emission function in eq. (1) and then decay exponentially in time according to their width. All matrix elements for the decays are assumed to be constant and thus the decay is determined by the phase-space only. In principle, one can derive the emission function that includes hadrons from resonance decays\(^3\) but the expression—unlike eq. (6)—is not suitable for massively multiple use in the fitting procedure.

Therefore, we generate stable hadrons and also resonances according to distribution \( S(x,p) \) and the assumption of chemical equilibrium. Resonances are then let to decay so that in the end we look only at stable hadrons. In our simulation we will systematically vary the temperature \( T \), transverse flow gradient \( \eta_f \), and the power \( n \). We construct histograms in \( p_t \) for some number of Monte Carlo events for each set of \((T, \eta_f, n)\) parameters which are then compared with measured data and a value of \( \chi^2 \) is obtained. This procedure is rather CPU and storage demanding because the generation must be done separately for each set of parameters that we want to check.

### III. Impact of Resonance Decays on Transverse Momentum Spectra

Data from Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV were measured by the ALICE collaboration. Spectra of the most abundant species—pions, kaons, protons and antiprotons—were published in \([10]\) along with a simple thermal fit of the spectra which included only directly produced particles and no resonance decay effect. An effort has been made to identify fiducial intervals in \( p_t \) where the influence of resonance decays can be omitted. They were \( 0.5 \) GeV/c < \( p_t < 1 \) GeV/c for pions, \( 0.2 \) GeV/c < \( p_t < 1.5 \) GeV/c for kaons and \( 0.3 \) GeV/c < \( p_t < 3 \) GeV/c for protons. As we first wanted to set the benchmark and compare our method to other analyses, we performed the same blast-wave model fit with the same fiducial intervals as \([10]\) using our Monte Carlo approach instead of eq. (6).

Event samples were generated for different sets of parameters \((T, \eta_f, n)\). The parameter space was sampled so that the step in temperature was 4 MeV, the step in \( \eta_f \) was 0.01, and the step in \( n \) was 0.02 or 0.04. Each of these steps induces roughly the same size of change in the resulting spectra. The step size was compromised in view of the CPU time required and has impact on the precision with which we can locate the parameter set that fits the data best. Parameter sets were chosen so that we always explore large enough region in parameter space around the best fit.

We checked that the generated spectra are accurately described by eq. (6) with appropriate parameters. Then we looked for the parameter set \((T, \eta_f, n)\) for which Monte Carlo data show the best match with measured data using the minimum \( \chi^2 \) method. Results are summarised in Table \( \text{II} \). They agree with those by ALICE collaboration \([10]\) reasonably well.

Then, in order to check whether resonances can in-
TABLE I. Freeze-out parameters obtained from fits to pion, kaon and proton $p_t$ spectra within fiducial intervals as defined in \cite{10}. Results without and with resonance decays included are compared to results by ALICE collaboration.

| centrality | ALICE \cite{10} $T$ [MeV] $\langle v_t \rangle$ $n$ | no resonances $T$ [MeV] $\langle v_t \rangle$ $n$ | with resonances $T$ [MeV] $\langle v_t \rangle$ $n$ |
|------------|--------------------------------|----------------|----------------|
| 0–5%       | 95 0.651 0.71                  | 98 0.645 0.73  | 82 0.662 0.69  |
| 5–10%      | 97 0.646 0.72                  | 98 0.645 0.73  | 94 0.654 0.69  |
| 10–20%     | 99 0.639 0.74                  | 102 0.637 0.73 | 90 0.649 0.71  |
| 20–30%     | 101 0.625 0.78                 | 102 0.624 0.79 | 98 0.633 0.75  |
| 30–40%     | 106 0.604 0.84                 | 110 0.605 0.81 | 102 0.616 0.79 |
| 40–50%     | 112 0.574 0.94                 | 110 0.572 0.97 | 118 0.581 0.89 |
| 50–60%     | 118 0.535 1.10                 | 122 0.527 1.15 | 126 0.541 1.03 |
| 60–70%     | 129 0.489 1.29                 | 126 0.484 1.39 | 146 0.489 1.23 |
| 70–80%     | 139 0.438 1.58                 | 142 0.439 1.51 | 170 0.425 1.55 |

FIG. 1. Ratios of hadrons coming from resonance decays to those produced directly for three different species. Monte Carlo data were simulated by DRAGON with the parameters $T = 98$ MeV, $\eta_f = 0.88$, and $n = 0.69$.

...deed be neglected in the fiducial range, we added resonance decays to our Monte Carlo data. We still kept the limitation to the fiducial $p_t$ intervals. Results are summarised in Table I. The extracted kinetic freeze-out temperatures changed and the direction in which they have gone depends on centrality. For central collisions the temperature was lowered while for peripheral ones it went up. It thus seems that leaving out resonances is not a good approximation even if one tries to identify a reasonable fiducial range for the fitting.

To support this statement we have analysed our Monte Carlo events and looked at the number of hadrons emitted directly and the number coming from the decays of resonances. In Fig. 1 we plot the ratio of hadrons produced from the resonance decays to those produced directly as functions of $p_t$. They are calculated for model parameters which best fit the spectra in most central collisions (see Table I). The portion of resonance production is very important not only for pions but also for kaons and protons. Moreover, the ratio shows nontrivial $p_t$ dependence. One might omit resonances in the fitting procedure in a region where these ratios are constant but there is no such interval for any of the investigated species. For pions the $p_t$-dependence is even non-monotonic. Hence, leaving out resonances is an invalid simplification.

IV. FITS OF HADRON TRANSVERSE MOMENTUM SPECTRA

In our actual analysis we fitted spectra of pions, charged kaons, protons and antiprotons \cite{10} together with spectra of $K^0$'s and $\Lambda$'s \cite{12}. Our simulations were further compared with spectra of multistrange baryons $\Xi$ and $\Omega$ published in \cite{18}. Finally, we compared with data \cite{14} our predictions for $K^+$ and $\phi$ which were based on the results of fits to $\pi^\pm$, $K$, $p$, $\bar{p}$, and $\Lambda$.

The $K^0$ and hyperon data are divided into fewer centrality classes than data from $\pi$, $K^\pm$, $p$, and $\bar{p}$. In order to make consistent fits which include all species, we used the centrality classes of hyperon spectra and summed up corresponding centrality bins in pion, kaon, and proton spectra. Error bars of experimental data points were taken as statistical and systematic added in quadrature.

Our analysis was performed with resonance decays always included. Chemical composition was specified by $T_{ch} = 152$ MeV and $\mu_B = 0$ \cite{13}. Note that shifting these values slightly is not expected to cause a big change in the shape of the transverse momentum spectra. The parameter space $(T, \eta_f, n)$ was sampled as described in the previous section. After having all ensembles of events simulated we compared them with data. Histograms of simulated data were normalized individually so that their normalization matches that of experimental spectrum. Among all simulated ensembles we found the one which best agrees with the data (the minimum $\chi^2$).

Fit results depend on the cuts imposed on the spectra. For each species we specified a high-$p_t$ cut. This is justified, because from some value of $p_t$ upwards hadrons are expected to be more influenced by hard production processes and not described by the thermal model we use. To find the cuts we determined ratios of measured-to-
simulated bin content $R_i = \frac{N_i^{\text{exp}}}{N_i^{\text{MC}}}$ for each species $i$ as a function of $p_t$. Then, those bins from the high-$p_t$ end of the spectra for which the value of $R_i$ was outside the range (0.9, 1.1) were excluded, effectively introducing high-$p_t$ cuts (the chosen range was found to lead to best fits). In the next step, Monte Carlo data were again compared with the data without excluded bins. This time, new high-$p_t$ cuts were determined and the procedure was repeated again. The iterations were stopped when they converged to one set of parameters and certain set of cuts.

For pions, we imposed also a low $p_t$ cut at 400 MeV/$c$, thus not including the first 9 bins into the comparison. We found that the quality of the fit significantly deteriorated without this cut. It seems that pion spectra show an enhancement here which might be due to non-equilibrium pion chemical potential not included in our simulation.

Here we did not try to come up with a fit function using Tsallis distribution that would cover the whole $p_t$ interval \cite{19, 20}. Its interpretation in terms of thermal model would be unclear.

### A. Spectra of $p, \bar{p}, \pi^\pm, K^\pm, K^0, \Lambda$

We first fitted $p_t$ spectra for the most abundant species: pions, kaons, (anti)protons, $K^0$s, and $\Lambda$s. In Fig. \ref{fig:spectra} we show positions of the best fits for each centrality. Note that in the actual fitting procedure we determined three parameters: $T$, $\eta_f$, and $n$. In order to compare results in a relevant way we have plotted here the positions of the best fits in just two parameters, $T$ and $\langle v_2 \rangle$, with the latter calculated from eq. (4) for the values of $n$, $\eta_f$ that give the minimum of $\chi^2(T, \eta_f, n)$. As can also be seen in Table \ref{table:fits} with the change of centrality $\langle v_2 \rangle$ sometimes changes due to a change in $n$ and not in $\eta_f$. In Table \ref{table:fits} the fitted values are displayed together with their $\chi^2$ and the number of degrees of freedom. In Fig. \ref{fig:spectra} they are displayed together with our estimates for the uncertainty region for the best fit values. We stress that these are only estimates because the evaluation of $\chi^2$ in discrete points does not allow us to determine them more precisely. We observe that the position of minimum determines very precisely the value of $\langle v_2 \rangle$. For the temperature the uncertainty is larger. It may range up to 10–15 MeV from the minimum.

We illustrate the quality of the fits in Figs. \ref{fig:fits} \cite{37}. For brevity, for the most abundant spectra we not only the comparison with positively charged species but note that the comparison looks the same for negative species. For pions (Fig. \ref{fig:fits}) we clearly see the enhancement at low $p_t$. Recall that our fitting procedure does not include any chemical potential but we account for resonance production. For pions at $p_t$ below 400 MeV/$c$, resonance contribution grows as $p_t$ is lowered. This can be observed in Fig. \ref{fig:fits}. Still, although qualitatively this behaviour might agree with what is seen in data, quantitatively it is not sufficient to explain them. Resonances tend to populate low-$p_t$ region but this is not enough to fit the data. We speculate that the solution might be in introducing non-equilibrium chemical potential for pions. This would naturally occur if the hadron gas chemically freezes out at a temperature around 150–160 MeV and then cools down while keeping the effective ratios of individual species constant. We estimated that the pion chemical potential at kinetic freeze-out temperature might reach values around 100 MeV. This is not enough for Bose-Einstein condensation but modifies the spectrum considerably.

In the higher-$p_t$ region the pion spectrum is well reproduced up to about 2 GeV. This seems reasonable, as for higher $p_t$ we may see signs of hard production.

Charged kaons (Fig. \ref{fig:spectra}) are well reproduced in a similar $p_t$ interval without the need to leave out any bins at low

### Table II. The best parameter values resulting from fits to transverse momentum spectra of pions, kaons, (anti)protons, $K^0$s and $\Lambda$s.

| Centrality | $T$ [MeV] | $\eta_f$ | $n$ | $\langle v_2 \rangle$ | $\chi^2$/N$_{\text{dof}}$ |
|------------|-----------|----------|-----|----------------------|------------------|
| 0–5%       | 98        | 0.88     | 0.69| 0.654                | 0.214/194        |
| 5–10%      | 98        | 0.88     | 0.71| 0.649                | 0.266/197        |
| 10–20%     | 106       | 0.87     | 0.71| 0.642                | 0.272/210        |
| 20–40%     | 114       | 0.86     | 0.81| 0.612                | 0.294/202        |
| 40–60%     | 138       | 0.82     | 0.99| 0.548                | 0.347/195        |
| 60–80%     | 166       | 0.77     | 1.43| 0.449                | 0.449/168        |

### FIG. 2. Positions of best-fit values of $T$ and $\langle v_2 \rangle$ for transverse momentum spectra of $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$, $K^0$, and $\Lambda$ are shown by red +’s. Results go from central (upper left) to non-central (lower right) collisions, with centrality classes indicated in Table \ref{table:fits}. Around each best fit value we estimate the 99% confidence-level region. By blue ×’s we show results of fits to spectra of multistrange species, centralities are indicated in Table \ref{table:fits}. For multistrange species we estimate the 68% confidence-level regions.
FIG. 3. Transverse momentum spectra of $\pi^+$ for different centralities. To display all spectra in one figure we divide data from non-central collisions by factors 2, 4, 8, 16, and 32. Lower panels show the experiment-to-Monte-Carlo ratios $R_i = N_{\text{exp}}^i / N_{\text{MC}}^i$ which demonstrate the agreement of measured and fitted spectra. Different panels correspond to different centralities. Horizontal lines indicate the interval $0.9 \leq R_i \leq 1.1$ to which we limit our fitting procedure.

$p_t$. We also observe good fits to (anti)proton spectrum (Fig. 5) stretching out even to about 4 GeV. In general, the agreement becomes slightly worse when going away from central collisions. For the most peripheral class charged kaons depart from the theoretical curve above 2 GeV/$c$ and protons above 3.5 GeV/$c$.

In the fit we also included strange $V^0$'s which were measured up to $p_t$ of 4.5 GeV/$c$ [12]. The kaons show (Fig. 6) similar behaviour as their charged isospin partners. When comparing the two plots for $K^+$ (Fig. 1) and $K^0$ (Fig. 6) one should notice the different $p_t$ intervals in which these spectra are measured. Below the $p_t$ cut of 2 GeV also the $\Lambda$'s are fitted well (Fig. 7). They slightly depart from this agreement above 2 GeV, but in a different way than other species: $\Lambda$'s are steeper at high $p_t$ than the thermal fits. Note that the values of freeze-out parameters were determined in common fits to all 8 species, including $\Lambda$'s. We might be seeing here the beginning of the departure of strange baryon spectra from the scenario of common freeze-out. Note, however, that the departure occurs for $p_t$ above 2 GeV/$c$ where thermal hydrodynamically inspired model should not be given too much stress.

B. Spectra of $\Xi^-$, $\Xi^+$, $\Omega^-$, and $\Omega^+$

The departure from the fitted model of the freeze-out state of the fireball is clearly seen when we focus on $p_t$ spectra of multiply strange baryons: $\Xi^-$, $\Xi^+$, $\Omega^-$, and $\Omega^+$. We show only the spectra of baryons in Fig. 8 ($\Xi^-$) and Fig. 9 ($\Omega^+$). Results for antibaryons are similar. Note that these species were not included in the previous fitting procedure. In order to check whether they fit into the same description of the fireball we have simulated their spectra in DRAGON with the sets of parameters that come from the fits to $\pi$, $K$, $p$, $\bar{p}$, $\Lambda$ (Table II). These predictions are plotted in Figs. 8 and 9 by dashed curves. We notice that in general the data are steeper than the prediction. The data would thus indicate lower transverse expansion velocities and earlier freeze-out of multiply strange baryons [21]. Note, however, that for the
The best parameter values resulting from fits to transverse momentum spectra of $\Xi$ and $\Omega$.

| Centrality | $T$ [MeV] | $\eta_f$ | $n$ | $\langle v_t \rangle$ | $\chi^2/N_{dof}$ | $N_{dof}$ |
|------------|-----------|---------|-----|----------------|-------------------|---------|
| 0–10%      | 126       | 0.82    | 0.74 | 0.608          | 0.375             | 41      |
| 10–20%     | 138       | 0.81    | 0.85 | 0.568          | 0.325             | 41      |
| 20–40%     | 158       | 0.78    | 0.93 | 0.536          | 0.417             | 37      |
| 40–60%     | 174       | 0.76    | 1.11 | 0.489          | 0.497             | 33      |
| 60–80%     | 214       | 0.70    | 1.43 | 0.408          | 0.857             | 39      |

In order to quantify this statement we have performed common fits to the four multistrange baryon species: $\Xi^-$, $\Xi^+$, $\Omega$, and $\Omega$ and extracted their values of $T$, $\eta_f$, $n$ and corresponding $\langle v_t \rangle$. They are listed in Table III and compared with the other fit results in Fig. 2. This clearly shows the general effect that multiply strange baryons seem to decouple at higher temperature and weaker transverse expansion. The fitted spectra are compared to data in Figs. 3 and 4 by solid lines. Due to higher statistics, fit results seem to be driven by the $\Xi$'s rather than by $\Omega$'s. Although it is hard to support it statistically, it seems that the $\Omega$ spectrum is even steeper than the fit results. This would indicate even lower expansion velocity.

Looking at the most peripheral centrality class we notice that the measured data seem to be well reproduced by both sets of fit results. Note that the freeze-out temperature in peripheral collisions is higher than in the central ones. The spectra in those collisions are thus less sensitive to the mass of particles. What we see here is an illustration of the ambiguity in determination of $T$ and $\langle v_t \rangle$. Lower temperature can be compensated by stronger flow and vice-versa. When spectra depend on the mass, this ambiguity is usually resolved by different shapes of $p_t$ spectra of different species. Figure 2 indicates that statistically one can still resolve the fit to multistrange baryons as the uniquely correct result.

C. Spectra of $K^*$ and $\phi$

ALICE collaboration has also published transverse momentum spectra of resonances $K^*$ and $\phi$. Studying resonances may reveal information about the dynamics of the fireball. In order to simulate these resonances we have forbidden them to decay in our Monte Carlo gener-
ator since by default their decay is turned on. We simulated their spectra with the parameters from Table II and compare them with data in Figs. 10 and 11. Hence, they have not been fitted in our treatment. We observe reasonably good agreement of theory with data in centrality classes 0–20% and 20–40% and $p_t$ below 2 GeV/c for the $K^\ast$. For higher $p_t$ the data tend to be flatter than the theory.

The $\phi$ meson with its mass 1.02 GeV/$c^2$ is an important probe of fireball dynamics. If it is produced from the thermalized fireball at the common freeze-out, then its spectrum must be close to that of protons. In Fig. 11 we compare the data with predictions based on parameters from Table II. Data seem to be slightly steeper than the prediction. This is best seen in the ratios $R_i$ plotted in the lower panels of the Figure. Such a disagreement might indicate slightly earlier freeze-out from the fireball. Note, however, that the deviation of the prediction from the data is much smaller than in the case of multistrange baryons and no indisputable sign of earlier decoupling can be claimed.

FIG. 8. Transverse momentum spectra of $\Xi^-$ for centralities indicated in Table III. To display all spectra in one figure we divide data from non-central collisions by factors 2, 4, 8, and 16. Dashed curves show predictions based on parameters from Table III. For the most central bin we show two predictions calculated with parameters for centrality classes 0–5% and 5–10%; they differ very little. Lower panels show the experiment-to-Monte-Carlo ratios $R_i = N_i^{exp}/N_i^{MC}$ which demonstrate the agreement of measured and fitted spectra. Different panels correspond to different centralities. Horizontal lines indicate the interval $0.9 \leq R_i \leq 1.1$ to which we limit our fitting procedure.

V. CONCLUSIONS

The blast-wave model with hadron production from resonance decays included can well reproduce single-particle spectra measured by ALICE collaboration in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Resonance contribution leads to shifts in the values of freeze-out parameters. For central collisions our freeze-out temperatures tend to be lower than those extracted by ALICE [10]. On the other hand, the temperatures shift in the opposite direction for peripheral collisions. Shifts in $\langle v_t \rangle$ have smaller relative size.

Multistrange baryons show freeze-out at higher temperature and weaker transverse flow. This is consistent
with earlier decoupling from the spectrum. Note that such a behaviour is known from SPS \[21\] and RHIC \[22\] data, as well.

In fits to data from most peripheral collisions we obtain temperatures for kinetic freeze-out that are higher than what is usually assumed for the chemical freeze-out. On one side we can take this result as a parametrisation and the values of parameters are those which fit the data best. However, as soon as we want to interpret these values in the framework of some scenario for the fireball evolution, we may be witnessing limitations of the used model.

Similar fits were performed recently with the Cracow single freeze-out model \[16, 17\]. The main feature of that model is common chemical and thermal freeze-out with non-equilibrium fugacities introduced for strange and also non-strange species. Due to this, the freeze-out temperature fitted there is generally higher than our results. Note however, that their freeze-out hypersurface has a different shape. Naturally, this opens the question if one can distinguish between the two models. Perhaps femtoscopy can provide the tool for this task.

It is an intriguing speculation if the two approaches may be equivalent. The scenario we have in our mind when performing our fit is that matter hadronizes and cools down while being chemically frozen. This leads to the appearance of non-equilibrium chemical potentials for all species, i.e. chemical potentials that are not given by chemical potentials of conserved quantum numbers \[23\]. In the single freeze-out model, on the other hand, the system is born into the chemical non-equilibrium. We wonder how close to this non-equilibrium state the fireball comes in the cooling fireball scenario.

A comprehensive picture of the gradual fireball cooling should also include earlier decoupling of multistrange baryons.

The most important issue in this treatment now seems to be the inclusion of chemical potentials. They may have influence on the shape of $p_t$ spectra particularly for pions and we seem to observe the corresponding features in the data. This task will be addressed in a subsequent paper.
FIG. 11. Comparison of measured $\phi$ spectra [14] with the predictions based on fitted parameters from Table II. Stars in the legend indicate that the centrality classes 20–30% and 30–40% of experimental data are compared to predictions based on the fit for 20–40% centrality in pions, kaons and (anti)protons.

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