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Production of ^{4}He and $^4\overline{\text{He}}$ in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV at the LHC

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Abstract

Results on the production of ^{4}He and $^4\overline{\text{He}}$ nuclei in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV in the rapidity range $|\ y\ | < 1$, using the ALICE detector, are presented in this paper. The rapidity densities corresponding to 0–10% central events are found to be $\mathrm{d}N/\mathrm{d}y_{^4\text{He}} = (0.8 \pm 0.4\ (\text{stat}) \pm 0.3\ (\text{syst})) \times 10^{-6}$ and $\mathrm{d}N/\mathrm{d}y_{^4\overline{\text{He}}} = (1.1 \pm 0.4\ (\text{stat}) \pm 0.2\ (\text{syst})) \times 10^{-6}$, respectively. This is in agreement with the statistical thermal model expectation assuming the same chemical freeze-out temperature ($T_{\text{chem}} = 156$ MeV) as for light hadrons. The measured ratio of $^4\overline{\text{He}}/^4$He is $1.4 \pm 0.8\ (\text{stat}) \pm 0.5\ (\text{syst})$.

Keywords: Pb–Pb collisions; ALICE detector; LHC; Anti-nuclei

1. Introduction

The production of light (hyper-)nuclei, up to a mass number $A = 3$, has been reported already in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV at the Large Hadron Collider (LHC). This includes deuterons, ^{3}He and the hypertriton as well as their corresponding anti-particles [1,2]. The observed total yields can be described well by equilibrium thermal models [3–9], with only three free parameters: the chemical freeze-out temperature T_{chem}, the volume V and the baryo-chemical potential μ_B. The current best fit to the measured yields at the LHC, including results ranging in mass from pions up to ^{3}He, results in a $T_{\text{chem}} = 156$ MeV [10]. The measurement of the production yields of ^{4}He and $^4\overline{\text{He}}$ ($A = 4$) will put additional constraints on T_{chem}. Since the baryo-chemical potential is consistent with zero ($\mu_B = 0.7 \pm 3.8$ MeV [11]) at LHC energies,

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the expected anti-baryon to baryon ratio is unity. Therefore, also the ratio is expected to be close to unity for particles composed of (anti-)baryons, namely the anti-nuclei and nuclei [6].

Furthermore, $^4\overline{\mathrm{He}}$ is the heaviest anti-nucleus ever observed. It was discovered in Au–Au collisions at RHIC by the STAR Collaboration [12]. Out of 10^9 Au–Au collisions at centre-of-mass energies per nucleon pair ($\sqrt{s_{\mathrm{NN}}}$) of 200 GeV and 62.4 GeV, 18 $^4\overline{\mathrm{He}}$ have been detected. The corresponding yield at a given transverse momentum p_{T} is compared to the prediction of the thermal model [13] and the coalescence nucleosynthesis model [14] and found to be consistent with both. A confirmation of this observation is still pending as no other experiment has been able to detect the $^4\overline{\mathrm{He}}$ particle since then.

Coalescence models have been successfully used to describe the general trends of deuteron production [15–25] in relativistic nuclear collisions, albeit with a number of external parameters. These models are clearly challenged with the regular pattern observed in the production probability for light nuclei measured by the STAR [12] and ALICE [1] Collaborations. To extend the studies to A = 4 the measurement at LHC energies is obviously of great interest.

In this paper, the measurement of the production yield of the ^{4}He and $^4\overline{\mathrm{He}}$ nuclei with the ALICE apparatus is presented. Besides the increase in collision energy, the main difference with respect to the measurement by the STAR Collaboration is the usage of a six layer silicon vertex detector in ALICE. Together with the other barrel detectors this provides precision information on vertex position, particle identification and momentum. The determined yields are compared to thermal model expectations.

2. Detector setup and data sample

The two main detectors involved in the identification of the ^{4}He and $^4\overline{\mathrm{He}}$ particles are the Time Projection Chamber (TPC) [26] and the Time of Flight (TOF) detector [27], combined with the start time detector T0. In addition, V0 detectors ([28,29]) are used for centrality determination and the Inner Tracking System (ITS) [30] is employed for tracking and the discrimination between primary and secondary particles [1,31]. A full description of the ALICE detector can be found in [32], whereas the performance of the ALICE sub-detectors is reported in [33].

The measurement of the ^{4}He and $^4\overline{\mathrm{He}}$ particles is performed on the 2011 data set of Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. From this campaign, 38.7×10^6 events in a trigger mix of central, semi-central and minimum-bias events are used in this analysis. This leads to 20.7×10^6 events in the 0–10% centrality interval, 17.4×10^6 events in the 10–50% centrality interval and 0.6×10^6 events in the 50–80% centrality interval. The combined yields are extrapolated to the 0–10% centrality class with the procedure discussed in section 4.

3. Analysis

To ensure high tracking efficiency, high energy-deposit ($\mathrm{d}E/\mathrm{d}x$) resolution in the TPC and a good track matching between the TPC and TOF detectors, a set of selection criteria is applied. In order to select primary particles, the corresponding tracks have to originate from the primary vertex. The primary vertex position is estimated using the ITS and the TPC detectors. The resolution of the vertex determination is better than 50 μm in the xy-plane and 150 μm in the z-direction for charged particles with momenta above 1 GeV/c. To select primary tracks, the minimum distance from the vertex, called Distance-of-Closest-Approach (DCA), is required to be smaller than 1 cm along the z-axis, whereas the DCA in the xy-plane must not be greater than 0.1 cm. In addition, a hit in the TOF detector is required for a precise time measurement and only those tracks are used for the track reconstruction. The selection criteria are summarised in Table 1.

Table 1
Selection criteria applied for the ^{4}He and $^4\overline{\text{He}}$ analyses.

Track selection criteria	value
Number of clusters in TPC	$n_{\text{cl}} > 80$
Number of hits in ITS	$n_{\text{hits}} > 2$
TPC track quality	χ^2/cluster < 4
Acceptance in pseudo-rapidity	$\lvert\eta\rvert < 0.8$
Acceptance in rapidity	$\lvert y\rvert < 1$
DCA$_z$	DCA$_z$ < 1cm
DCA$_{xy}$	DCA$_{xy}$ < 0.1 cm
PID selection	**value**
TPC PID cut	$\pm 3\sigma$
TOF mass window	$\pm 3\sigma$

The $\mathrm{d}E/\mathrm{d}x$ is measured in the TPC as a function of the rigidity p/z, where p is the momentum and z is the electric charge in units of the elementary charge e. This distribution of reconstructed charged particles is well described by the Bethe–Bloch formula [34,35] and is unique for each particle species.

Primarily, all events with at least one particle with a $\mathrm{d}E/\mathrm{d}x$ corresponding to a ^{3}He and $^3\overline{\text{He}}$ or a higher mass are selected. To ensure a good track matching between the TPC and the TOF detectors, only candidates within 3 standard deviations (σ) around the mean in the $\mathrm{d}E/\mathrm{d}x$ (TPC) vs. $\beta\gamma$ (TOF) plane are accepted. Here, β denotes the relativistic velocity $\beta = v/c$ and γ is the Lorentz factor. In order to select ^{4}He or $^4\overline{\text{He}}$ particles, candidates within a 3σ band of the Bethe–Bloch parametrisation in the $\mathrm{d}E/\mathrm{d}x$ versus p/z distribution are taken into account. At higher momenta, the two Bethe–Bloch curves of ^{4}He or $^4\overline{\text{He}}$ and of ^{3}He or $^3\overline{\text{He}}$ approach each other. To study a possible contamination from ^{3}He and $^3\overline{\text{He}}$ particles, different narrower cuts for the TPC $\mathrm{d}E/\mathrm{d}x$ selection band are investigated: while the upper cut of the band (3σ) is fixed, the lower cut is restricted progressively going in steps of 0.5 units from -3σ up to 0σ. For all these seven cuts the procedure described in the following is carried out and a yield $\mathrm{d}N/\mathrm{d}y$ is determined.

In Fig. 1, the velocity (β) distributions of He candidates are plotted versus rigidity. One can clearly see the separation of ^{3}He and ^{4}He. From these data, the m^2/z^2 (m = mass of the particle) distributions are calculated and displayed in the insert of this figure. From the insert, the separation of ^{3}He and ^{4}He can be quantitatively asserted. The m^2/z^2 is different for ^{3}He (2.00 GeV$^2/c^4$) and ^{4}He (3.48 GeV$^2/c^4$). Candidates lying within a window of 2.86 GeV$^2/c^4 < m^2/z^2 <$ 4.87 GeV$^2/c^4$ are identified as ^{4}He or $^4\overline{\text{He}}$ particles. This window is determined by a fit to the peak in the m^2/z^2 distribution of the selected tracks. Because of the low statistics, the fitting is done simultaneously both for particles and for anti-particles, including secondary ^{4}He knocked out from the material. A Gaussian with an exponential tail on the right side is used as the fit function. For the background, the sum of a first-order polynomial and an exponential shape is assumed. This is necessary to describe the time-signal shape of the TOF detector [27]. The polynomial shape is needed to cope with mismatched candidate tracks in the signal region. A similar procedure is used in [1].

For the analysis of positively charged ^{4}He, contamination from ^{4}He nuclei which do not originate from the primary vertex, but stem from the detector material due to knockout processes, are taken into account. Monte Carlo studies suggest a cut on $p/z > 2$ GeV/c to eliminate such

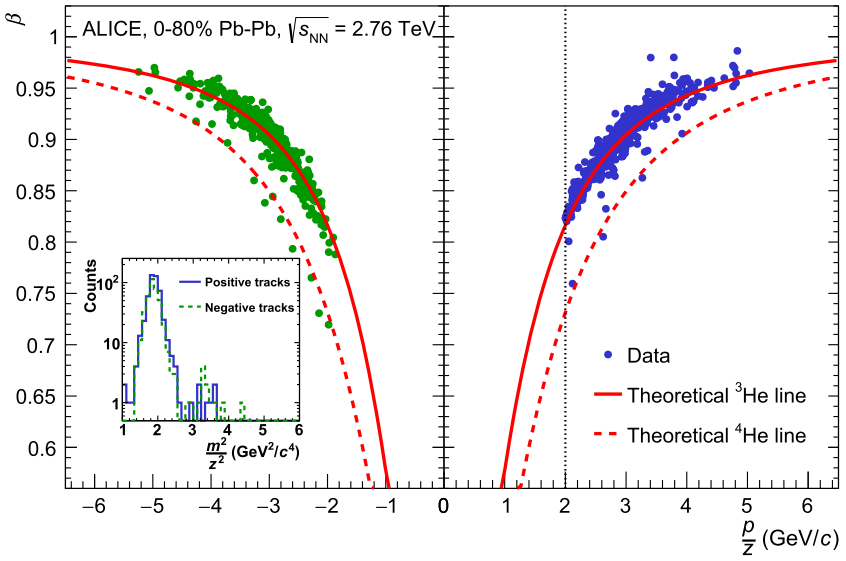

Fig. 1. Velocity β measured with the TOF detector as a function of the rigidity p/z. For this figure a selection band of -1.5 to 3σ around the mean of the TPC specific energy-loss distribution is required. Negatively (positively) charged particles are shown on the left (right) side, with positive tracks in blue and negative tracks in green. The dashed vertical line represents the cut on the rigidity $p/z = 2$ GeV/c (applied only for positively charged particles). The insert shows the m^2/z^2 distributions obtained from the data points shown in the main figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a background. Note that the background due to knockout processes is steeply falling with momentum and the signal is rising in this momentum range. Therefore, only ^{4}He candidates with a p/z greater than 2 GeV/c are accepted. The contamination at higher momenta is estimated to be a maximum of 0.13 counts out of a total count of the order of 10, which is added as a systematic uncertainty.

The small number of clear signal counts observed by combining the TPC and TOF information does not give any indication of background. In order to estimate an upper limit on the background counts from mismatched tracks in the TOF detector underneath the ^{4}He or $^4\overline{\text{He}}$ peak in the TOF mass window, a likelihood fit under the assumption of a flat background is performed in the $\mathrm{d}E/\mathrm{d}x$ versus $\beta\gamma$ plane outside the $\pm 3\sigma$ matching band. In this way, background candidates are identified as mismatched particles. (These are usually rejected and only used for this purpose.) Due to limited statistics, this procedure cannot be used if a stronger selection criterion is applied for the TPC $\mathrm{d}E/\mathrm{d}x$ selection, since no ^{4}He or $^4\overline{\text{He}}$ candidates are left to apply this technique. For these particular cases, we assume a constant ratio of ^{3}He to background counts and use this to estimate the number of ^{4}He background.

The background stemming from misidentification of (anti-)^{3}He as (anti-)^{4}He is estimated to be more than one order of magnitude smaller than the one from the mismatch of TPC tracks when extrapolated to the TOF detector and is therefore considered to be negligible. The estimated background decreases with more stringent TPC $\mathrm{d}E/\mathrm{d}x$ cuts. The signal-to-background ratio improves depending on the tightness of the $\mathrm{d}E/\mathrm{d}x$ cut from 1.7 to 8.4 for ^{4}He and from 1.7 to 17.6 for $^4\overline{\text{He}}$.

To estimate the efficiency for the detection of ^{4}He and $^4\overline{\text{He}}$, a Monte Carlo simulation is generated in which the kinematical distributions of the particles are generated flat both in rapidity

y and in transverse momentum p_{T}. The shape of p_{T} spectra in heavy-ion collisions is typically described by a blast-wave model [36]. This model assumes an average radial-flow velocity $\langle\beta\rangle$ and a kinetic freeze-out temperature T_{kin} as described in [37]. Generally, most hadron p_{T} spectra measured in heavy-ion collisions can be described well by one common set of parameters [38]. Surprisingly, this also works well for the description of deuteron and ^{3}He p_{T} spectra [1]. Hence the same prescription is used here for the p_{T} shape of ^{4}He and $^4\overline{\mathrm{He}}$ particles, namely the same set of parameters is used, only the mass is changed to the ^{4}He mass.

Since only a small number of ^{4}He and $^4\overline{\mathrm{He}}$ particles (14 $^4\overline{\mathrm{He}}$ and 9 ^{4}He for the widest TPC $\mathrm{d}E/\mathrm{d}x$ cut) are observed, a p_{T} spectrum can not be measured. It is estimated using the blast-wave parameters of deuterons and ^{3}He spectra [1]. The final acceptance $\times$ efficiencies are obtained as described in [39] and are of the order of 15% for ^{4}He and 20% for $^4\overline{\mathrm{He}}$. The difference originates from the 2 GeV/c rigidity cut applied to ^{4}He candidates.

For the $^4\overline{\mathrm{He}}$ analysis, the absorption in the detector material is taken into account using two different transport codes, namely GEANT3 [40] and GEANT4 [41]. These two codes use different models for the estimation of the absorption cross section. In GEANT4, a Glauber model based on the well known hadronic interaction cross sections for (anti-)protons is implemented [42]. The version of GEANT3 used in this analysis is modified [1] such that it calculates the absorption based on an empirical parameterisation [43], based on the measurements of anti-deuterons carried out at Serpukhov [44]. The baseline is given by the absorption calculated with GEANT4, while the GEANT3 based correction is used in the systematic uncertainty evaluation. The maximum absorption probability towards low p/z is about 20%. In contrast to GEANT4, which still shows an absorption of about 5% at $p_{\mathrm{T}} = 10$ GeV/c, GEANT3 exhibits basically no absorption above 3.5 GeV/c.

The main contributions to the systematic uncertainty on the determined production yields are:

- The uncertainty due to the unknown shape of the p_{T} distributions, which is determined by using the blast-wave model based on the measured deuteron and ^{3}He spectra [1]. This leads to a systematic uncertainty contribution of around 13%.
- Only for ^{4}He: The rigidity cut on p/z greater than 2 GeV/c itself has a systematic uncertainty of 4 to 13% depending on the TPC PID cut. As mentioned before, the secondary contamination above this cut is estimated to be a maximum of 0.13 counts. This leads to a systematic uncertainty of at minimum 20% and at maximum 49% growing with stricter TPC PID cut. As the number of observed candidates shrinks with stricter TPC $\mathrm{d}E/\mathrm{d}x$ selection, the systematic uncertainty on the secondary contamination grows.
- Only for $^4\overline{\mathrm{He}}$: The absorption correction has an uncertainty of 7%, estimated from the difference of the two GEANT implementations.

Other systematic uncertainties are estimated by varying the cuts in the limits consistent with the detector resolution. The contributions of these systematic uncertainties are typically found to be below the percent range. The systematic uncertainty on the chosen TPC PID cut varies between 1% for the most loose cuts and 19% for stricter cuts. This is caused by the stronger sensitivity of the stricter cuts, namely the even further reduced low number of candidates, which is not reflected in the Monte Carlo simulation.

The final values and the corresponding uncertainties are calculated as a mean from the previously discussed variations of the selection criteria. The resulting systematic uncertainty on the final yield is 35% for ^{4}He and 20% for $^4\overline{\mathrm{He}}$.

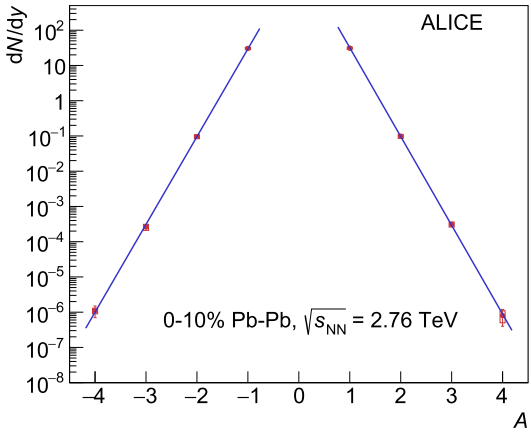

Fig. 2. dN/dy for protons (A = 1) up to ^{4}He (A = 4) and the corresponding anti-particles in central (0–10%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The blue lines are fits with an exponential function. Statistical uncertainties are shown as lines, whereas the systematic uncertainties are represented by boxes.

4. Results

The measurement is performed on a data set including central, semi-central and minimum-bias triggered events. To make use of all the data analysed, the semi-central and minimum-bias events have been extrapolated to 0–10% centrality interval assuming that the particle and anti-particle yields scale linearly with the charged-particle multiplicity d$N_{\rm ch}$/dη. This procedure has already been tested to work well for the (anti-)hypertriton production [2]. In addition, d/p and ^{3}He/p ratios are measured to be approximately flat versus multiplicity within uncertainties [1]. Thus, for each centrality class, the number of analysed events is multiplied by the corresponding measured charged-particle density d$N_{\rm ch}$/dη [28]. If this is added up and divided by the total number of measured events it leads to a weighting factor of 1034. To get the final yield in the 0–10% centrality class the measured yield is multiplied with the d$N_{\rm ch}$/dη for 0–10% centrality (1447.5) and divided by the weighting factor, as $\mathrm{d}N/\mathrm{d}y_{0-10\%} = \mathrm{d}N/\mathrm{d}y_{\rm measured} \times 1447.5/1034$.

This leads to final values of $\mathrm{d}N/\mathrm{d}y_{^4\mathrm{He}} = (0.8 \pm 0.4\ (\mathrm{stat}) \pm 0.3\ (\mathrm{syst})) \times 10^{-6}$ for ^{4}He and $\mathrm{d}N/\mathrm{d}y_{^4\overline{\mathrm{He}}} = (1.1 \pm 0.4\ (\mathrm{stat}) \pm 0.2\ (\mathrm{syst})) \times 10^{-6}$ for $^4\overline{\mathrm{He}}$. For the ratio $^4\overline{\mathrm{He}}/^4$He we obtain $1.4 \pm 0.8\ (\mathrm{stat}) \pm 0.5\ (\mathrm{syst})$ ("stat" and "syst" indicate the statistical and the systematic uncertainty).

The measured yields in the 0–10% centrality interval are shown in Fig. 2 together with those of (anti-)protons, (anti-)deuterons and (anti-)^{3}He [1,38] (details on the extrapolation to 0–10% centrality can be found in [10]). The blue lines are exponential fits with the fit function Ke^{BA} resulting in $B = -5.8 \pm 0.2$, which corresponds to a penalty factor (suppression factor of production yield for nuclei with one additional baryon) of around 300. The same penalty factor is also obtained if the fit is done up to ^{3}He only [1].

The obtained penalty factor of around 300 for each additional nucleon is consistent with $T_{\rm chem} \approx 160$ MeV in the equilibrium thermal models. The measured yields for ^{4}He and $^4\overline{\mathrm{He}}$ nuclei are consistent with the predictions from the various (equilibrium) thermal models (THERMUS [45], GSI [5,46,47] and SHARE [48–50]) with $T_{\rm chem} = 156$ MeV, as shown in Fig. 3 for complete statistical thermal model fits using the available light flavour data measured by the ALICE Collaboration. The fits in Fig. 3 extend the simple exponential model (Fig. 2) by incorporating Boltzmann statistics and degeneracy factors for all particles. If instead of all listed

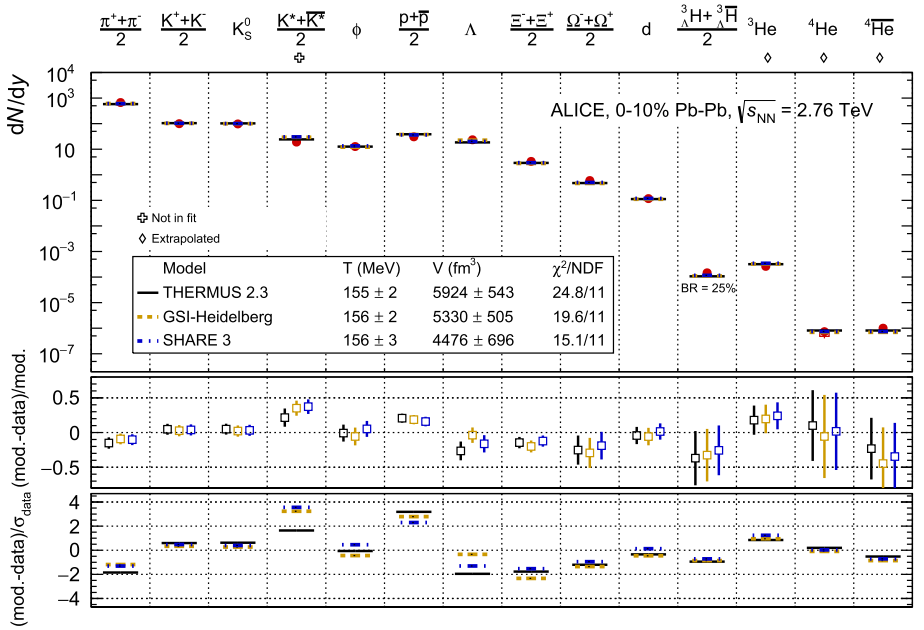

Fig. 3. Thermal model fits, with three different implementations, to the light flavour hadron yields in central (0–10%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The data points are taken from [1,2,38,51–54] and details of the fits can be found in [10,11]. The upper panel shows the fit results together with the data, whereas the middle panel shows the difference between model and data normalised to the model value and the lower panel the difference between model and data normalised to the experimental uncertainties.

particles only nuclei (deuterons, ^{3}He and ^{4}He and $^4\overline{\rm He}$) are considered for the fit, the resulting temperatures are 154 ± 4 MeV. The pure measured yields for ^{4}He and $^4\overline{\rm He}$ nuclei agree, depending on the model implementation, within the determined uncertainties with temperatures from 135 MeV to 177 MeV. Taken together these observations suggest that the relatively heavy ^{4}He and $^4\overline{\rm He}$ nuclei are also produced statistically at the same temperature as the lighter particles.

5. Summary and conclusion

The ALICE Collaboration has measured the production yields of ^{4}He and $^4\overline{\rm He}$ in central (0–10%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The ratio of the two yields is consistent with unity and the results are in good agreement with the prediction of the statistical thermal model assuming the same temperature of 156 MeV as is obtained from the fit to the other light flavour hadrons.

Data gathered at the current beam energy of $\sqrt{s_{\rm NN}} = 5.02$ TeV in Pb–Pb collisions at the LHC (*Run* 2) will improve the studies described in this letter thanks to an increase in statistics by a factor of about 3. Based on the pilot measurement presented here, we conclude that a precision study will be possible in the data taking period starting from 2021 (*Run* 3 of the LHC), where about 5500 ^{4}He ($^4\overline{\rm He}$) particles are expected to be reconstructed [55]. This will allow for the measurement of the transverse-momentum spectra. As the unknown shape of the $p_{\rm T}$ distributions is one of the major sources of the systematic uncertainty, the measurement of the spectrum will decrease the systematic uncertainty of the measured yield. As a consequence the precision of

the ratio of $^4\overline{\mathrm{He}}/^4\mathrm{He}$ will be significantly improved. In addition, a mass difference measurement similar to what was done in [56] will be possible.

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